AE1-C

Single-Ended

Stereo Tube Amplifier Kit

DV0221

Analog Ethos™

WARNING: RISKS OF ELECTROCUTION OR FIRE

Be safe with this amplifier kit! Follow all instructions carefully in this manual, and for your safety, please take seriously the risks and follow the precautions below. By purchasing this kit and assembling it yourself, you have personal liability to ensure safety in the building and operation of the amplifier. DIY electronics is a great hobby, but it comes with risks including but not limited to those below.

Important risks:

- This amplifier uses mains voltage (120 VAC) which can **kill you** if you touch it and current passes through you.
- This amplifier uses a power transformer to create a **high voltage** power supply up to **500 volts DC** which will **kill you** if it passes through you, will destroy your finger or screwdriver if you touch it and create a short circuit. Do not think this voltage is safe in any way to touch with your hand or a tool.
- This amplifier uses **capacitors that are charged** when the amplifier is on and may not be discharged even when the amplifier is off and unplugged, even hours or days later, if not bled properly. These capacitors hold sufficient energy at high voltage to **seriously injure or kill** you.
- Vacuum tubes and power transformers create **high heat which can burn you** if you touch the surfaces that reach hundreds of degrees Fahrenheit. There is a **risk of fire** if the amplifier is in an enclosed space without adequate ventilation, or other objects are touching or near the tubes or transformer.
- You will need to utilize a soldering iron to build your amplifier, which operates at a very **high temperature** and will burn you if you touch it, or can **cause fire** if not properly used.
- The amplifier is **heavy**, and it requires a sturdy table or stereo shelf to hold it safely.

Follow these general safety precautions:

- Never plug in or operate your amplifier with the chassis open. Do not attempt to trouble-shoot the amplifier while turned on. Use safe inspection methods only when the amplifier is off, unplugged, and capacitors are discharged. Never assume insulated wire or components inside the amplifier are safe to touch while the circuit is live.
- Do not leave an exposed circuit accessible to other people, especially children or pets.
- Keep a clean work space, with no wires or other objects near your amplifier or soldering iron.
- Follow all safety instructions for your soldering iron. Unplug when not in use. Allow safe time and space to cool.
- Utilize a non-conductive work table and mat below your chair or standing position.
- When turning on your amplifier for first use after building, use a power strip switch and follow instructions to monitor for smoke, smells, sounds, or other indicators of a problem. Immediately turn off power if you detect any.
- Never leave the amplifier turned on and unattended. Always turn it off when you leave the room or your home.
- Operate your amplifier on top of a table or sturdy stereo shelf with at least 12 inches of space above the top of the vacuum tubes, and 6 inches of space around each side of the amplifier chassis. For proper ventilation, ensure the bottom perforated panel is not obstructed and the amplifier rests on the chassis feet.
- Do not place the amplifier inside of an enclosed cabinet or stereo console that has limited ventilation. The amplifier gets very hot and requires air flow to stay at a safe operating temperature.
- If you have a child in your home, do not operate the amplifier in a location where the child can reach it. It takes only a second to get a serious burn from the tubes which will glow and may attract the interest of a child.

Table of Contents:

Introduction

So, you are ready to build a DIY point-to-point hifi stereo tube amplifier? Maybe you have read about tube amplifiers or are a curious learner and have been wanting to make the jump into this hobby, or perhaps you have already built DIY electronics in the past and want to learn more and build a new great-sounding amplifier with high quality design and components. Maybe you are experiencing something in your life and need an escape from the day-to-day and you want to put your mind and hands to work on something to take you away from it for a while.

Whatever your situation, I'm glad you decided to give this a try! Here are the goals I had when I created this kit. Hopefully this matches what you are looking for.

Goals for this kit:

LEARNING

You will truly learn how a vacuum tube amplifier works.

This is not simply a step-by-step guide, although you could use it that way. My intention is to show you exactly how the entire circuit works, how each component is selected and the role it plays. You will walk away with knowledge that empowers you. This may be the only kit you build, or it may be one stop on a journey of learning and building. Perhaps your next build will extend on what you have learned, and you could customize a circuit or come up with your own designs. If you want to learn, this is the kit for you!

As you can see, the instructions are extensive and filled with illustrations, photos, and explanations. Some kits include poorly written instructions that are difficult to follow, and you might get the amplifier to work, but only after frustration, perhaps a few mistakes, and certainly without learning anything new. I want your experience with these instructions to be the best you've ever had in a kit!

HIGH QUALITY AUDIO

You will get high audio quality, with reasonable circuit complexity and cost.

First, I am using a straightforward single-ended circuit, mostly to achieve the objective above for you to learn how it works. Before moving on to more complex circuits that could provide higher output power or other characteristics, you should know how a triode tube amplifies the signal, understand rectification and filtering of a power supply, basics of negative feedback, and several other elements. The circuit used here is customized for the components included, but is not unique, and is based on designs that have been used for many years and proven to work very well. I have carefully tested it and made adjustments, with performance shown on subsequent pages.

One of the benefits of a kit is that you have everything you need in one box, and don't need to go through the difficult job of sourcing components, often from multiple suppliers, paying multiple shipping costs and needing to identify precisely the right part from a multitude of options, sometimes testing and needing to try again with a different selection. This work is done for you so you can save time, money, and avoid mistakes.

I have sourced high quality components for this amplifier from carefully selected manufacturers, for the best possible quality without entering into areas of excessive cost. There are many "audiophile" products sold at outrageous prices, and with dubious claims of performance. I'm sure you've seen them—fancy and enormously thick speaker wire or interconnects, rare new-old-stock tubes, magical capacitors, and other items that add up to many thousands of dollars. This kit amplifier will sound excellent and be reliable, at a cost that is reasonable without compromises. There are cheap components available and used in other tube amplifier kits that you may find on auction sites or other distributors. I did not try to build the cheapest possible kit, and I assume you are someone who is willing to pay for quality.

This amplifier is perfect for typical listening in a home, with relatively low distortion and minimal hum, though it is not a high power amplifier. If you build this kit, learn how it works, and want to build something for louder output or lower sensitivity speakers, you can expand to other more advanced circuits such as a push-pull design, or try other tubes and components.

VISUAL DESIGN

How it looks is as important as how it sounds.

Great visual design is important to have an end-product you are proud of. This is a showpiece in your home that your friends and family will see and ask about. I wanted to create a custom-designed chassis to hold the components functionally but also beautifully in context of your listening environment. Inspired by mid-century modern designs, the kit includes a carefully crafted hardwood box and aluminum top and back panel that perfectly fit the transformers, tubes and physical layout of the circuit.

For those of you who don't have extensive workshop tools and finishing capabilities, this allows you to have a great-looking amplifier and not settle for an off-the-shelf, generic metal box.

But for those of you who do have tools and skills of design and construction, this kit can serve as your entry into point-to-point building. I will explain how the layout is selected and important choices about the physical construction to minimize hum and ensure heat dissipation or other considerations. You may in the future build a custom design of your own for your next amplifier and put some of your own inspiration into it! Tube amplifiers are both art and science, and I hope you'll lean into your creative side. Along the way, I'll share a few thoughts on design, inspiration and craftsmanship.

What you need to get the most out of this kit:

- **Basic soldering skills (and a few hand tools).** You will need to solder some wires and small components in enclosed spaces. It's not always easy, and I'll share tips along the way. You don't need extensive soldering experience, but should be able to get good and clean connections in order to have a safe and functional amplifier.
- **Relatively high-sensitivity speakers.** While you can drive any 8-ohm speakers with this amplifier, you will experience the best sound with speakers that are ideally higher than 90 dB SPL. The amplifier will typically provide around 5-7 watts of power per channel for a standard consumer line level source. This may surprise you if you are used to solid-state amplifiers that may advertise 50 or 100 watts per channel or more, which may be necessary to drive low-sensitivity speakers at low distortion levels. We'll get into this later! Just know that if your speakers are below 90 dB SPL, you may not get ideal output and distortion levels.
- **Patience!** Take your time and enjoy the process. Read and observe carefully to put the right parts in the right places. If you make a mistake along the way, take a step back and try again. There are few mistakes that can't be corrected if you catch them in your process, but if you don't follow the instructions and checks carefully, it's possible you will damage components along the way or when you turn on the amplifier.

Notes on safety and information included:

As indicated on page 2 of this manual, there are important risks to be aware of with an electronics hobby. Hopefully you know that already! Most importantly, tube amplifiers operate at very high voltage. In this case, between 400-500 volts DC, which is more than enough to kill you in a brief moment. These instructions do not have you doing any work or testing on a live circuit.

This manual gives you instructions to build the amplifier in a safe manner using a limited set of common tools and a soldering iron. Along the way, I will provide additional tips and suggestions for builders who may be interested in expanding into a more extensive hobby, or in the theory and testing methods behind the design of this kit. This manual cannot possibly go into all the details of safe testing methods that could involve use of multimeters, oscilloscope, spectrum analyzer, variable transformer, and others. If you are a trained technician or have experience working with high voltage, it is at your own risk (I know you know this!) if you choose not to follow these instructions or elect to perform other tests using additional equipment.

When I build and test amplifiers, I do sometimes access an exposed circuit using test equipment. You should not expect to do this at all with this kit. However, so that you can understand some elements of safety, below are examples of protective steps I take:

- I use an isolation transformer so that any exposed mains voltage is less likely to have a path to ground if I were to accidentally touch it.
- I use a variable transformer ("Variac") to slowly bring up voltage to test a circuit
- Turning on an amplifier on my work space requires multiple separate power switches, so others in my house can't easily turn on a high voltage circuit. I keep these all off when I leave the room.
- I have a rubber mat beneath my work space as a ground insulation.
- I manually discharge capacitors using a resistor after turning off a circuit, or double-check the discharge is done even if a bleeder resistor is in place.
- I never, ever put more than one hand over a circuit to probe with a multimeter. I force myself to hold a small object in one hand to avoid instinctively reaching in with it (some people follow the rule of putting one hand in their pocket). Current from one hand to the other would pass through my chest (heart) and has greatest risk of death. Brushing across a high voltage potential with one hand could still cause injury but is less likely to be lethal.

You can learn more about safety through many other sources. A healthy respect for electricity and the risks outlined on page 2 are very important. I hope you'll have an enjoyable hobby, but please be safe, for your sake and those around you!

Parts list

Note on parts: Most of the small parts are provided in labeled bags. At times I buy different brands of resistors or capacitors, depending on suppliers I'm using, which means they may be different color or appearance than the pictures below, but they will always be the same type and rating. Resistors are all metal-film or wirewound types for lowest possible noise. Colors of the chassis, volume knob, and output transformer covers may also vary depending on special designs I may make available, and I may provide options for tube brand selection. All other parts will be as shown. The important thing to remember is to carefully identify the part using the label on the bag, and to not get resistors confused, especially those marked using color bands instead of printed values. Putting the wrong resistor in the wrong place in the circuit will cause serious problems and damage to components. I suggest you double-check resistance using a multi-meter to ensure the correct part.

Hammond 290DX
Power Transformer

(2) SE 5k Ohm Primary
Output Transformers

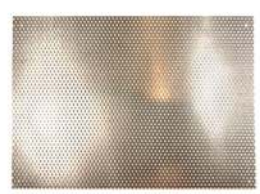
Hammond 159Q
6H 200mA Choke

Amplifier chassis
with aluminum top

(2) EL34 power tubes

12AT7 dual-triode tube

Aluminum back panel



Perforated aluminum
bottom panel

(2) 8-pin tube sockets

9-pin tube socket

(2) RCA connectors
black and red

(2 pairs) speaker terminals
black and red

 Fused AC power entry IEC connector	 AC power cord	 2A slow-blow fuse	 (4) rubber grommets
 220uF 500V electrolytic capacitor	 30mm capacitor mounting bracket	 56uF 500V electrolytic capacitor	 (2) 33uF 500V electrolytic capacitors
 (2) 220uF 50V electrolytic capacitors	 (2) 100uF 25V electrolytic capacitors	 (2) Auricap XO 0.22uF 600V film capacitors	 (2) 1200V Rectifier diodes
 CL-70 NTC Thermistor	 Volume knob	 100k Alps dual-gang logarithmic potentiometer	 Power switch

(13) ring terminals

(3) 5 lug terminal strips
(3) 4 lug terminal strips
(2) 3 lug terminal strips

(2) 500 Ohm 5W
Resistors

(2) 470 Ohm 1W
Resistors

(2) 47k Ohm 3W
Resistors

(2) 1k Ohm 1/2W
Resistors

(2) 100 Ohm 2W
Resistors

(2) 2.7k Ohm 1W
Resistors

(3) 220k Ohm 2W
Resistors

(2) 180k Ohm 2W
Resistors

(2) 1M Ohm 1/2W
Resistors

(2) 3.3K 2W
Resistors

shielded
2-conductor wire

Hookup wire
multiple colors and lengths

Zip ties and heat shrink
tubing for wires

Various hardware / fasteners
(not all shown here)

Tools and Workspace

You will need the following tools to assemble the amplifier:

- Phillips and flat head screwdrivers of several sizes
- Nut drivers/sockets or wrenches for #4, #6, #8 nuts
- Wire stripper for 18-22 gauge wire (kit includes all wire you will need)
- Soldering iron with medium chisel tip. I suggest a 40 watt pencil-style iron, or a temperature-controlled solder station. Have a sponge or wire tip cleaner, too.
- Electrical solder. I suggest Kester 0.8mm 63/37 tin/lead rosin core solder.
- Side-cutters or other small snips for trimming leads
- I suggest small needle-nose pliers for shaping leads, and tweezers for holding or maneuvering wire or components in place
- Ideally you have a digital multimeter for double-checking resistance of individual components and connectivity (while the amplifier is off)
- I also suggest some type of “helping hands” tool with alligator clips or other method to hold wires or items in place as you solder them

An ideal workspace is a flat table or work bench with good lighting and room for your soldering iron to sit in its holder without risks of touching other objects or being bumped into your lap. There should generally not be a cat residing on this table. Have plenty of space to lay out the instructions and components you are working with. If you don’t have a dedicated work bench, the kitchen table is fine. Tell your family that your amplifier is more important; they will understand.

To hook up and operate your amplifier, you will need:

- A pair of speakers and speaker wire (never operate the amplifier without speakers or load hooked up, or you may cause damage to the amplifier). For best results, I recommend speakers with at least 90 dB rated sensitivity, and speaker wire 16 awg or heavier.
- A line-level audio source (CD player, computer audio output, phone/tablet with headphone output, etc.) and audio connector wire with RCA jacks. This amplifier does not have a phono stage driver and will not directly amplify a turntable unless you have a separate pre-amplifier for the phono source.

To enjoy your amplifier in operation, you will need:

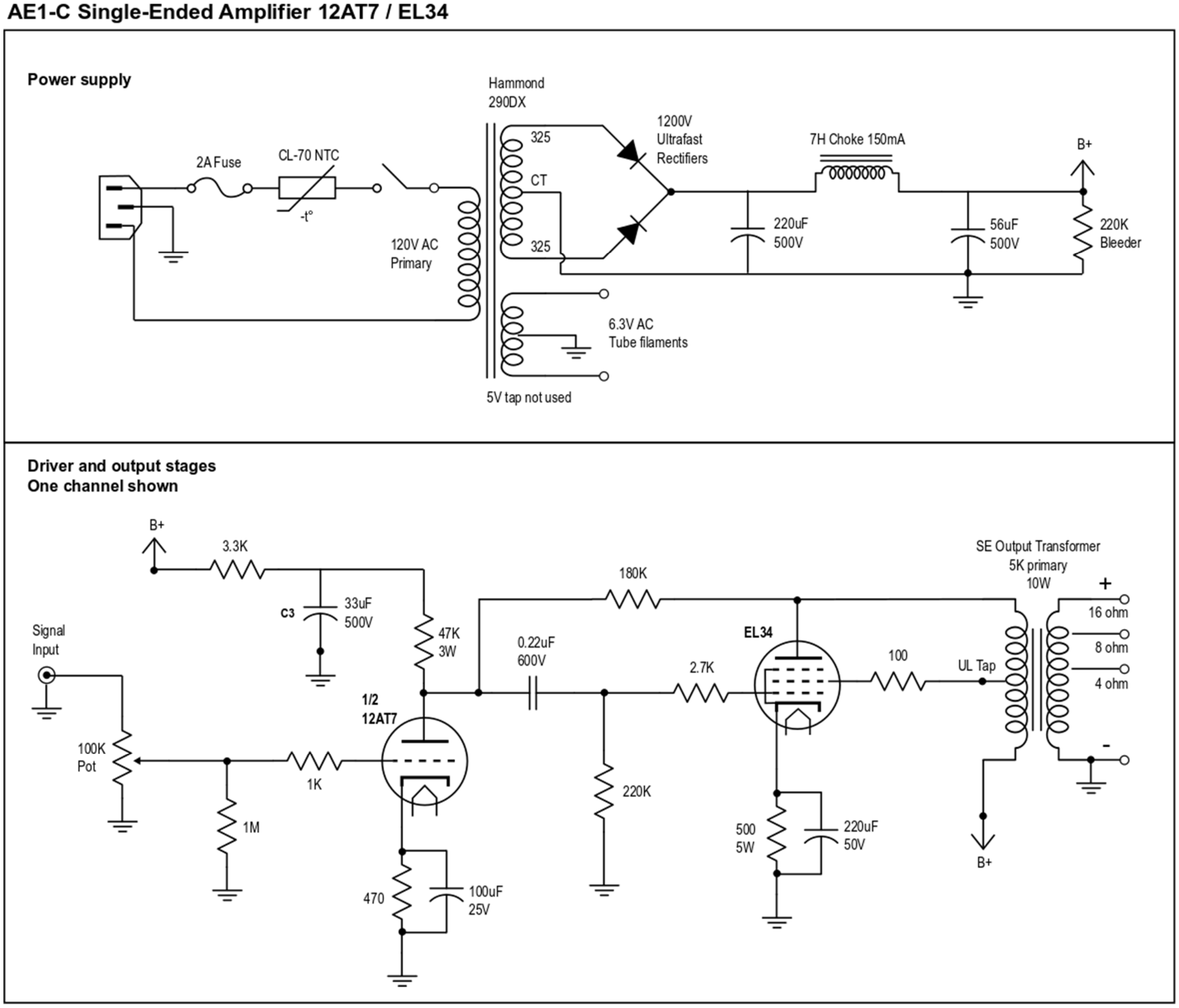
- A great album to play. I like Diana Krall for a first listen.
- Comfy chair, preferably with a cat in your lap.
- Celebratory drink. I recommend gin and tonic with fresh lime.

Circuit Schematic

You do not need to know how to read a schematic to build the amplifier, but it will certainly help you understand and learn if you can try to follow it. The schematic here shows the power supply and one of the driver/output amplifier channels. Because this is a stereo amplifier, the amplification portion of this circuit would be replicated identically, one for the left channel and one for the right.

This is based on a commonly used single-ended circuit design[1], but it is customized to work well with the components selected for inclusion. We will walk through the details of this schematic in Part II of this instruction manual.

AE1-C Single-Ended Amplifier 12AT7 / EL34



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[1] This schematic is customized for this kit and can't be easily referenced to a single source, but is certainly not unique. It has similarities to versions created or used by many others in various DIY communities or from proven circuits used for many years. Many individuals share their knowledge, talents and experiences so we all can learn and try new versions. I do not take credit for this design.

Tested Performance

Below are the tested results I was able to measure. Note that results will vary due to different vacuum tubes having different characteristics or changing over time as they age, components having tolerances, mains voltage slightly different in different houses, my test equipment is not high-end in accuracy, and other reasons. These tests are done using dummy loads, and of course actual operation is with speakers that have varying impedance and their own performance results.

All that to say, take these measurements as examples for purposes of learning about amplifier performance, not as any guarantee of the results you'll get.

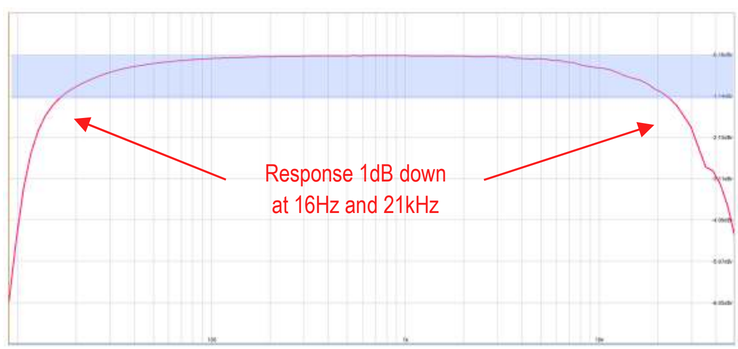
Summary measures from my tests:

- Maximum Power Output: 7 watts per channel
- Total Harmonic Distortion 0.4% @ 1W (1kHz)
- Input Sensitivity: 850mV RMS
- Frequency response: 16 Hz – 21 kHz (<1dB)

Detailed measurements

Frequency Response

This shows a frequency response across a wide audio range. It is within a small tolerance of 1dB (blue band) from about 16Hz to 21kHz. While very few speakers have response down as low as 20Hz, and you typically can't hear up to 20kHz, we want this to be as accurate as possible within 1dB across the audio spectrum.

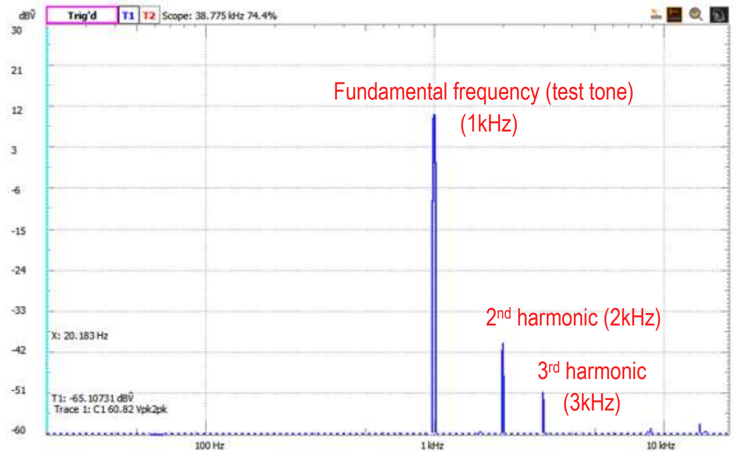


Harmonic distortion typical profile

What you see here is typical of a single-ended tube amplifier. At a moderate listening level, you will see some second and third order harmonic distortion typically adding up to around 0.5-1% THD.

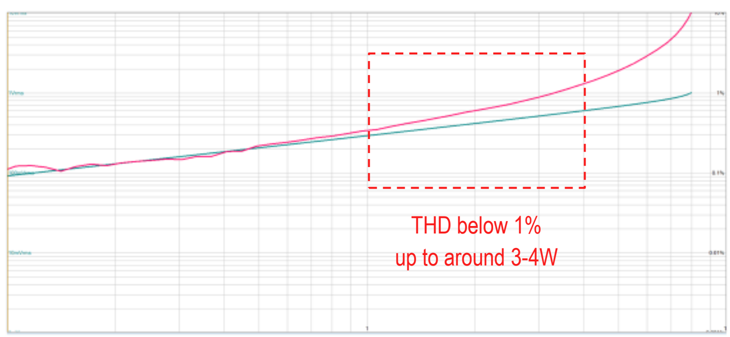
The fundamental frequency here is 1kHz, and you can see the 2nd harmonic is about -50dB relative to FF and 3rd harmonic about -60dB relative. Second and third order harmonics are usually considered more acceptable to our hearing than higher-order distortion. There are few higher order harmonics except at very high output levels from a strong input signal and amplifier at full volume.

You'll also note on this frequency analyzer chart that there is no evident sound at 60 or 120Hz, common spots to watch for ground loops or insufficient power supply filtering.



THD to Power

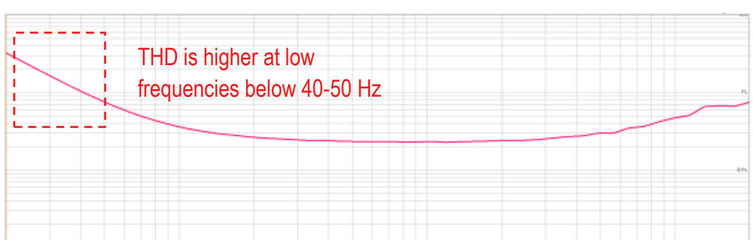
This chart shows how distortion is proportional to output power. This is not a high-powered amplifier, but you can get very good sound with only a few watts. With a sufficient input signal you can run the amplifier up to about 7 watts before THD starts to rise to 3-5% or higher



THD to Frequency

This is just interesting for you to see that distortion is highest at low frequencies, especially below around 40Hz. In this low-power test it is above 1%, relative to about 0.2 – 0.3% for higher frequencies.

Combine this insight with the fact that distortion rises with power, and you'll understand that you could have most distortion in very low, loud audio output.

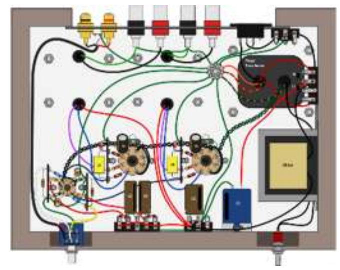


Part I: Build Instructions

Ready to build?

I personally think it would be best if you read Part II first, learn how the tube amplifier works, and then build it. But I know it's hard to wait and I didn't want you to see that section with all the details and maybe get turned off! You don't need to know how the amp works to build it (or perhaps you already know the theory), so by all means, c'mon and let's get started building! But if you have some patience, it could enhance your experience to read Part II first, and then come back to this section to build the amp. 😊

Read instructions carefully and ensure yours matches exactly what you read and see. In the appendix is a ***layout diagram*** *for your reference. Be sure to use this. Most photos will correspond to the orientation shown at right, where you have the amplifier upside down and are looking down into it, with the back of the amplifier away from you ("top" as shown). Also note that most of the photos are from the AE1, very similar to the AE1-C, but some wire colors and components will look different.*



Use layout diagram in the appendix

If you have any questions, please contact me via my website. I'll try to get back to you quickly. I want you to have all the info you need to build this. Have fun and take your time—have a nice drink and play some Led Zeppelin or something while you work. Don't try to do it all in one session. Remember building Legos? Yeah, it's not really anything like that, but those were fun, right?

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1 Insert the **four rubber grommets** into the holes on the **chassis**. Wires from the output transformers will eventually go through these holes, and the grommets protect those wires from rubbing against the metal edges. There are only four holes that will fit properly. You'll need to squeeze and push them into place using nimble racoon-finger manipulation on both sides of the panel.

(4) rubber grommets

Chassis

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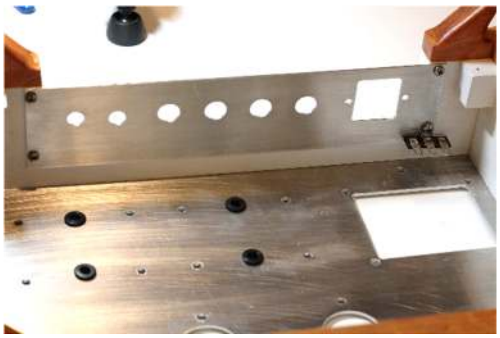
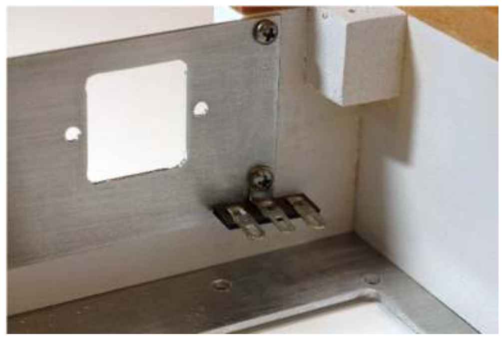
2 You will next screw on the **aluminum back panel** into the pre-drilled holes in the inside-back of the amplifier using four 3/8" pan head screws, but as you do it you will also attach a **3-lug terminal strip** on one corner underneath one of the screws. This will be used later to put a thermistor near the power inlet. Ensure that the smooth finished side of the aluminum panel is on the outside, and the square opening is in the upper right side as shown in the picture when looking from the inside of the amplifier toward the back. Make sure to use the pan-head screws (smaller and rounder heads) and not the truss-head screws (flatter, wider) which are used for another purpose.





Aluminum back panel

3-lug terminal strip

(4) #6 3/8" pan head screws

3 Attach the **star ground bolt** into the location shown. This is a 7/8" truss-head (wider, flat head) machine screw and you should use a flat washer, lock washer, and nut on the inside of the chassis. Tighten very securely. This will form a star ground point where multiple wires will connect to zero voltage potential. (There is an extra lock washer and bolt that you will eventually put on top to hold all of these down as a last step. You can temporarily put this loosely onto the screw so you don't lose it.)

This ground bolt also serves a safety purpose by grounding the top aluminum panel. If a high-voltage were to somehow be in contact with the top panel during operation, it would short to ground instead of creating a dangerous voltage that someone could touch. You will notice that we will ground all of the conductive panels—top, back, and bottom.

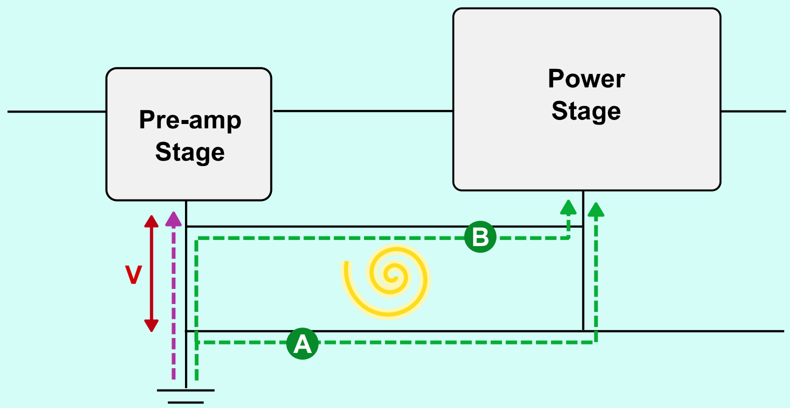
7/8" #6 Truss Head
Flat washer
Lock washer
Nut

(Additional lock washer and nut to eventually clamp down all grounded ring terminals)

Ground loops, hum and interference

Grounding is a form of magic that few but Gandalf truly understand, and even he knows only what the ancients have made knowable. In brief, you don't want **ground loops**, which are caused when there is more than one path to ground in the actual wiring of a device. This creates a loop sort of like an antenna that can easily pick up interference, commonly from AC magnetic fields at mains frequency (60Hz). Due to resistance in the wires, this can turn into a fluctuating voltage, causing an audible hum in the amplifier.

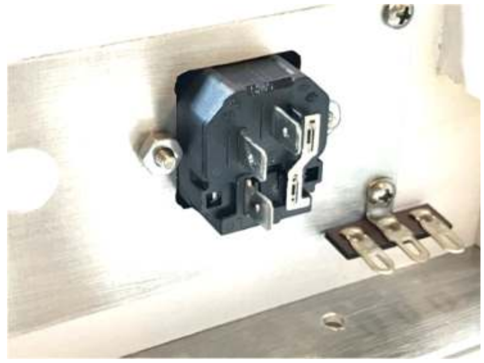
In a schematic, you see many ground points ⏚ where a part of the circuit is intended to be referenced to a zero voltage potential. In our actual wiring of the amplifier, we need to find a way to make this physical connection. You might think that any connection that leads to ground is at the same zero volt potential, but this isn't always the case. Consider the following:



Here you see that the power stage has two paths to ground—one direct (A) and one that shares a ground wire with the input pre-amp stage (B) (the pre-amp also has a loop not highlighted). This forms a ground loop that will pick up interference or stray AC magnetic fields that are created elsewhere in the amplifier. Because the wire connecting the pre-amp to ground has some tiny amount of resistance in it (all wires do), and current is flowing through that wire, there is a voltage potential (red arrow) that is modulated by the interference current, causing hum in the sensitive pre-amp stage. The solution is to break the ground loop by using only path A or B, not both. (Ideally A, so the power stage is not impacting the pre-amp).

In our case, we are using a **star-ground** technique to independently wire different parts of the circuit to a single ground point. There are other techniques that can be used, as well as considerations for how parts of a circuit might share a ground wire or not.

4 Attach the **IEC power inlet module** using the included #6 oval head screws, lock washers and nuts. Mount it so that the fuse tray is oriented to the top of the amplifier (or at the bottom, from your perspective with the chassis upside down on your work surface).



AC power inlet

5 Mount the **power switch** to the chassis on the same side as the power inlet (right side when upside down). There is a nut and lock washer that will stay on the interior side of the wood chassis, and a flat washer and cover nut that goes on the outside. The threading has a slot that should orient toward the bottom of the amplifier and the washer has a tab that faces outward; this prevents the washer from rotating and damaging the surface as you tighten the nut. Be careful to not scratch the outside of the chassis as you use an open-end or adjustable wrench to get it tight. Ensure it is aligned vertically.

Power switch

Some switches have a standard nut on the outside that is easier to tighten with a wrench, but that would look rather ugly, don't you think? This one has a more finished-looking round nut, with barely noticeable flattened edges for a tool to tighten. It is a bit trickier to install. Be aware that the nut is not designed to screw on more than a short distance. If you can't get it tight enough to hold the switch in place, you need to back off the interior nut so less threading is exposed on the outside. As another tip, you may find it easier to get the outside nut started if you hold the toggle switch half-way between its up/down state.

Once you have it securely in place, give yourself a high-five. You are awesome.

6 Time for some soldering. Yeah, baby. You'll need some of the 22 awg **hookup wire** and two **ring terminals**. I've given you lengths of hookup wire in different colors, but you'll need to cut them to length and strip each end. For this step, you will use:

- 4" green wire, and one ring terminal
- 3" green wire, and one ring terminal


(2) Ring terminals


Green hookup wire

We need to attach a ring terminal to one end of each of the green wires. These will be ground wires, one for safety earth to the power inlet and the other as a safety ground for the aluminum back panel. Do not skip these steps because you think safety is for babies. This is not optional.

I use a helping hands tool as you see in the picture below while I solder one end of each green wire to the small hole in a ring terminal. The clips help to hold it steady while you solder. If you don't have one of these, you can probably manage by finding some other way to get the wire and ring terminal to stay steady while you solder.

You will repeat this process in several other places for additional ring terminals later. I won't show the details again, knowing you are a clever person and can remember.

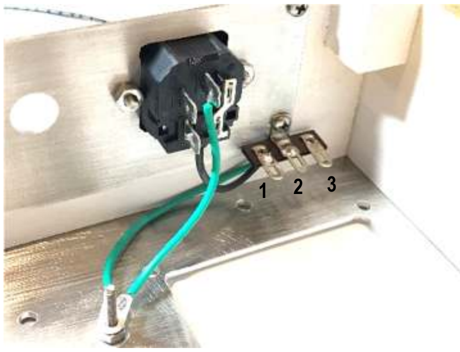
7 In this step, you will use the **two green wires** you prepared in step 6, and you will also need to cut and strip some additional **22 awg wire**:

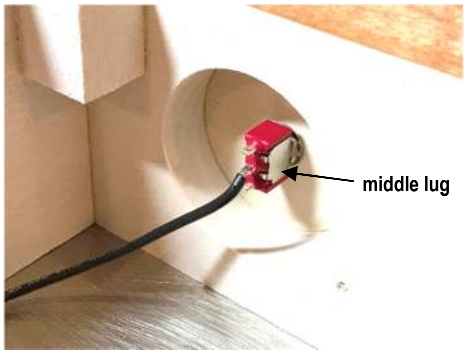
- 2” black wire
- 11” black wire

Black hookup wire

Don’t confuse this black hookup wire with the thicker 20 awg heater wire or the black shielded wire that we will use later and are marked in their own bags. Solder these connections:

- The 4” green wire is soldered to the middle lug (lug 2 in photo) of the 3-lug terminal strip. We are using this lug as a way to ground the back panel. It’s best to bring the wire up from the bottom through the hole closest to the screw, so it’s out of the way. The other end of this wire with the ring terminal will go over the ground bolt.
- The 3” green wire is soldered to the safety earth of the power inlet, this is the top connector in the middle. The ring terminal of this wire also goes over the ground bolt.
- The 2” black wire is soldered to the live power inlet, after the fuse. You can see the power will come in on the location marked with an “L” for live, which is then passed across the fuse section to the connector you will use. The other end of this wire goes to the nearest lug on the terminal strip (lug “1” in photo), using the hole closest to the back panel, leaving free the outer part of this lug which will be used later for the thermistor.
- The 11” black wire is soldered to the far-right lug of this terminal strip (lug “3”), through the hole closest to the back panel. This leaves free the outer lug which will be used for the other side of the thermistor. The other end of this black wire is routed along the edge of the chassis up to the power switch and is soldered to the middle lug of the switch.





8 Trim and bend the leads of the **thermistor** to fit across the 3-lug terminal strip and solder from lug 1 to lug 3, skipping over the grounding lug in the middle. Ensure the leads are relatively short and allowing the thermistor to stand in place with air around it. It gets hot and you don't want this component near anything. This is another time when I often use a helping-hand clip to hold the component in place while I solder.

Thermistor

Be aware also that the leads and lugs are exposed and will eventually carry mains voltage, which is dangerous. You would never want to accidentally touch these while the amplifier is in operation. Many electronic devices will cover mains voltage connectors with protective sleeving. There are too many points with high voltage potential in this amplifier to try and cover them all, so it is safest to not operate and work inside this amplifier with the power on.

What is a thermistor?

This is a "negative temperature coefficient" or NTC thermistor, which means that when it is cold, it acts like a resistor—in this case with 16 ohms of resistance. As it heats up over a few seconds, the resistance drops, down to around 1 ohm or less. We use it here to limit inrush current when the amplifier is first turned on. When the capacitors are not yet charged and the core of the power transformer is not yet magnetized, there can be a large current in the first second or so, and the thermistor will control this a bit and avoid putting strain on components or blowing fuses.

Inspection point

Take a moment and double-check all of your connections so far. No stray wires touching anything? Any excess leads are trimmed neatly? No solder has dripped or spread where it shouldn't be? Solder joints are secure with no movement? Did you connect the wires to the correct locations?

You are having fun so far? Need a refill on your drink? Album needs to be flipped to side B?

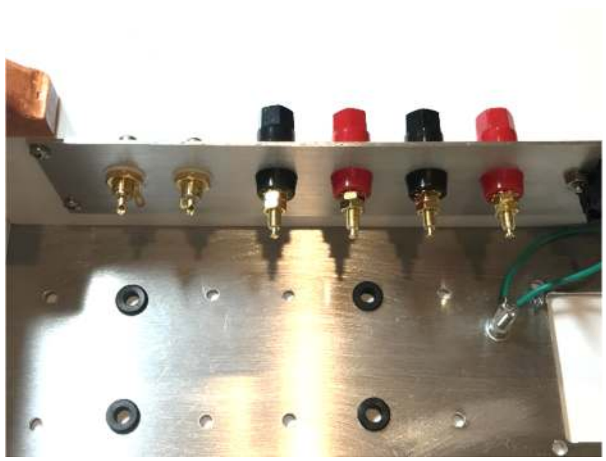
9 Install the **RCA jacks** and **speaker binding posts** in the back panel. Convention is that black is left and red is right, and remember you are working with the amplifier upside down. Each of these has plastic spacers, one for the outside and one for the inside, to clamp tightly in place and prevent the inner conductive parts from touching the aluminum panel. (Note that the AE1-C has binding posts that look different than the ones in the picture here.)

RCA jacks

Speaker binding posts

The RCA jacks will later have their outer conductors grounded together to the same wire, so tilt the metal terminal lugs slightly toward one another and pulled away from the back panel so there is room to work with them.

Align the binding posts so that the lug tips are turned upright to hold solder and the speaker wire holes are vertical in case you use speaker cable without a banana plug, it will be easier to insert. (I think life is too short to screw on speaker wires, so I recommend banana plugs!)



10 Mount the choke to the side wall of the chassis near the power switch using 3/8” truss head screws into the pre-drilled holes. Orient it so that the wires are coming out of the top, so they are accessible for a later step. Tighten the screws in place.

Choke

(2) 3/8” truss head screws

11 Mount the **capacitor bracket** to the inside front of the chassis, using two 3/8” pan head screws into the pre-drilled holes next to the power switch. Orient it so that the clamp screw is on the top, accessible later.

Capacitor bracket

(2) 3/8” pan head screws

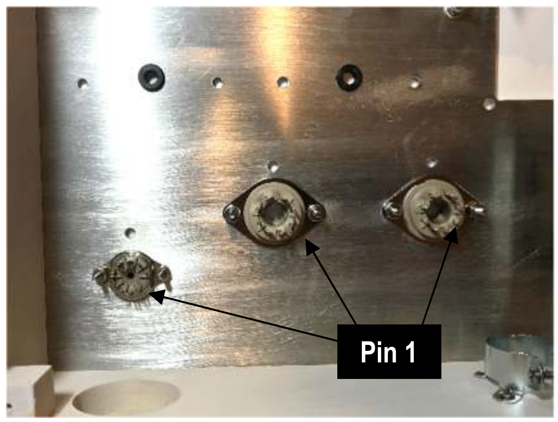
12 Mount the **tube sockets**. The smaller, 9-pin (noval) socket will use two #4 truss-head machine screws with corresponding lock washers and nuts. The two larger 8-pin (octal) sockets use #6 truss-head machine screws with lock washers and nuts. The hardware for the tube sockets is in the same bag with them. (Note that there are a few extra lock washers and nuts you will use in the next step for terminal strips that are mounted on these same screws.)

(2) 8-pin tube sockets with hardware

9-pin tube socket with hardware

Important! It's critical to orient these properly to have the correct wiring to the pins of the tube. The pins are numbered on the sockets if you look closely. Mount them so that the low numbers (1, 2, 3…) are closer to the front of the amplifier. The sockets mount from the underside of the aluminum chassis plate, with the screws coming down from the top.

It is easy to scratch the aluminum top, so be careful as you insert the screws through the top panel, then through the tube socket brackets (the larger sockets may take some nudging and rotating of the screws to go through), and then put on the lock washers and nuts. I prefer to hold the screws steady with a screwdriver and tighten from the bottom with a nut driver or wrench.

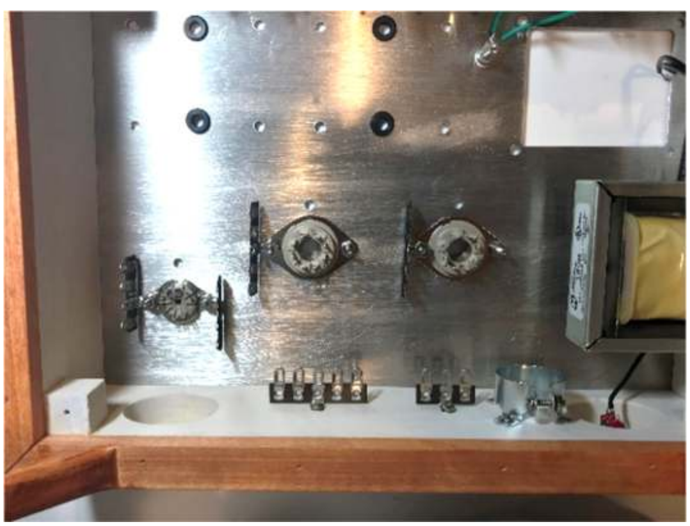


Inspection point

Take one more look. Is pin 1 of each tube socket closest to the front of the amplifier? You're doing a good job. I don't care what anybody says.

13 Mount additional **terminal strips** for the tube sockets and power supply filter section. The 9-pin tube socket gets two 4-lug terminal strips, one on each side, with a lock washer and #4 nut to secure it on top of the existing bolts and nuts holding the socket. The 8-pin power tubes each get a single 5-lug terminal strip on the left-hand side (closest to the 9-pin socket), with a #6 lock washer and nut. We will later be soldering wires and components between the pins of the tube socket and these terminal strips.

There are two additional pre-drilled holes in the front of the chassis for a 5-lug terminal strip on the left and 3-lug terminal strip on the right, closest to the capacitor bracket. Use a 3/8" pan-head screw to secure these in place. These brackets will hold several resistors and capacitors as part of the filtering of the power supply.



(2) 4-lug terminal strips

(3) 5-lug terminal strips

3-lug terminal strip

(2) 3/8" pan head screws

14 Mount the **power transformer** to the chassis. With the transformer upside down on your workspace, feed the bundle of wires through the rectangular opening (be aware that stripped or tinned wire leads can easily scratch the top aluminum plate), and insert the four existing bolts through the holes, allowing the transformer to fit through the opening until the existing transformer nuts are resting against the chassis top. There is a manufacturer label on the power transformer that you can orient toward the back of the amplifier. This includes specifications of the transformer that are useful for future-you to have the voltages and ratings of the different windings, but you could remove this if you prefer.

Power transformer

(4) #8 Flat washers
Lock washers
Nuts

Since the chassis will now be a few inches off the table with the transformer underneath, you will want to put some type of (non-scratching) object underneath to support the chassis while you tighten the nuts. A few thick books, or whatever works. In a later step, I'll suggest ways to work on the amplifier when it has its transformers all installed.

Use four #8 flat washers, lock washers and nuts provided together in a bag for the power transformer hardware, and secure the transformer in place using its existing bolts. A nut driver is the best tool for this, especially due to the corner that is difficult to reach, but you could use a wrench or needle-nose pliers. Ensure it is tight.

Orientation of transformers

Don't you like this lay-down style transformer? It just looks cool. I chose it specifically instead of an upright transformer based on visual design of the amplifier. But it serves another purpose in orienting the core of the transformer on a different plane than the output transformers, to keep induced hum to a minimum. Transformers cause a magnetic field to be created and the output transformers could pick up some induced current if they are physically too close, resulting in a low hum at the 60 Hz frequency of the mains AC voltage. Distance is one way to avoid this, as well as rotated orientation of the cores.

15 In this step you will trim and solder several of the power supply leads. See the chart for descriptions of the colors and how we will use them.


(3) Ring terminals


Heat shrink tubing

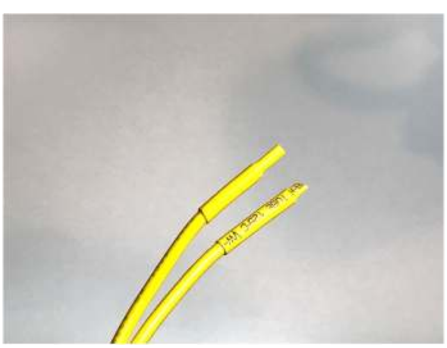

Nylon zip tie

Cut the **two yellow leads** and the **red/green-stripe lead** down to a shorter length, say 3-4 inches. Put a piece of heat-shrink tubing (included) over each end and heat it to shrink with a heat-gun or by holding the barrel of your soldering iron near it. This is for safety to ensure it doesn't accidentally touch anything. Tie it in a loop with the small zip-tie. Someday if you re-use this transformer, you'll still have the leads accessible, but this keeps them out of the way for now.

Power Transformer Lead Colors and Usage

2 black	These are the primary side of the transformer and they receive the mains voltage (120VAC).
2 red	These are the high voltage secondary AC (~650VAC, or +/- 325V relative to the center tap). We will use to rectify into DC voltage.
red w/ yellow stripe	This is the center tap of the secondary high voltage winding. This will be our 0 voltage potential reference for all ground points in our circuit and will go to our star ground point.
red with green stripe	This is a 50V bias tap used in some amplifiers, but we will not use it, and will cut and tie it off.
2 green	These are the 6.3VAC secondary windings for the tube filament (heater) supply. This will go in parallel to each of the tube sockets.
green w/ yellow stripe	This is a center tap for the 6.3V supply; we will reference this to our 0 volt star ground.
2 yellow	These are a 5VAC secondary winding, typically used for the filaments of a rectifier tube. Our amplifier is using silicon diodes instead of a rectifier tube, so we will not need this 5V supply, and will cut and tie this off.
orange	This is an electrostatic screen in between the primary and secondary windings of the transformer. It's used to reduce the transfer of noise from primary to secondary. We will connect it to ground.

Trim the **red/yellow-stripe**, **green/yellow-stripe**, and **orange** leads down to about 4-6 inches, long enough to reach our star ground bolt. Strip these wires and solder a ring terminal onto them as you did before. Place these three onto the ground bolt. This provides the 0-volt reference for our high voltage circuit, references the heater center tap to it, and grounds the electrostatic shield.



Trim **one black lead** to a short length, about 3-4 inches, so it reaches neatly to the power inlet. Strip and solder this to the Neutral connector, on the upper left, marked on the plastic module with an N.

Trim the **other black lead** to about 8-9 inches, long enough to route it underneath the choke and up to the power switch. Solder it to the top lug on the power switch (as viewed with the amplifier upside down).

Keep wires short, but workable

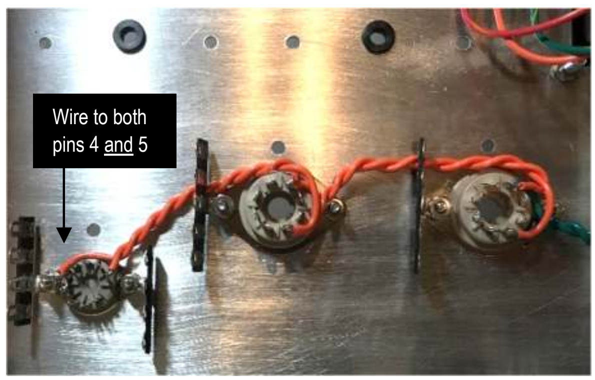
Throughout the course of this build, your wires should be as short as possible. This not only keeps your work neat and organized, but it reduces resistance and capacitance in the wires, and limits risks of picking up interference or rubbing against a hot component. But give yourself a bit of latitude with the length, in case you make a mistake and need to re-strip a lead, and to be able to navigate the wires a bit. Don't make it into a spider web of tight wires without any flexibility. Several steps will also include some important instructions for certain wires that are either sensitive or carry AC currents that could cause hum.

16 Time to twist some heater wires. It's a rite of passage for all tube amp builders. You will be awesome at this, I know it.

20 AWG heater wire

Start with the **two green wires from the transformer**. This is the 6.3V power supply for the tube filaments. Twist these wires together and shape it to lead up to the right-hand side of the nearest 8-pin socket. Trim the leads and solder these to pins 2 and 7, using the bottom holes in the lugs.

Next, use the **black 20 awg heater wire** and cut into four pieces about 6-7" long each. (Note that the other colors of wire are 22 awg, so it's important that you use the heavier gauge wire marked in its own bag. Also, I previously used orange wire, shown in the photos here, but have switched to a black polyolefin type that I really like because it's easier to twist and shape.) Twist these wires and arrange so you can run a parallel connection from the first tube socket to the second one. Shape and trim the wire carefully; one lead will be longer than the other. Fit into place and solder using the top holes from the first socket and bottom holes of pins 2 and 7 of the next socket.



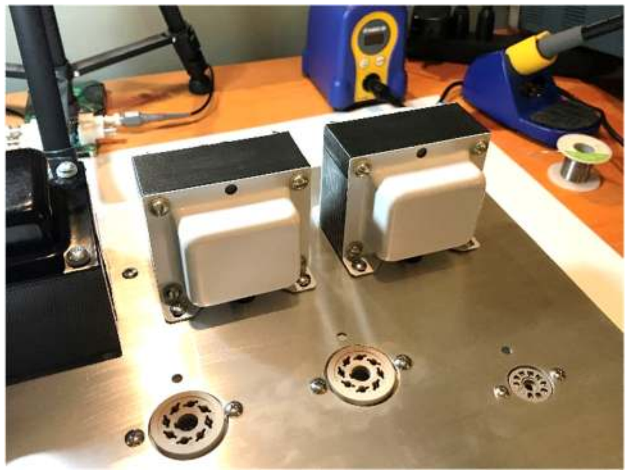
Do this again, over to the 9-pin driver tube socket. The 12AT7 has more than one voltage option; in our case you'll need to connect one of your wires to <u>both pins 4 and 5</u>, and the other wire to <u>pin 9</u>. One option is to strip the wire a bit longer and solder it to both pins. But it's sort of hard to align the wire, so I suggest you trim a little lead clipping from the 56uF capacitor and bend it into a U-shape and solder to bridge pins 4-5. (we need to trim those leads later anyway). See the illustration here.

My photo here is probably tighter than ideal, you could use more length to give yourself more room to keep the filament wiring a bit further away from the tube sockets.

Why am I twisting wires?

Tube filaments take high currents to heat up—EL34 tubes draw 1.5A each, and 300mA for the 12AT7. This comes from the transformer at 6.3V AC at 60 cycles per second (US). If we aren't careful, this can create interference with sensitive audio signal wires, amplified and heard as a hum. In some circuits, the filament power might be rectified into DC voltage to avoid this. Our circuit leaves this as AC, but by twisting the wires, we put in close proximity the alternating sides of the voltage so magnetic fields cancel each other out. Routing wires carefully is also important, avoiding heater wires running alongside other wiring, crossing where needed, minimizing proximity.

17 Mount the **output transformers**. Feed the wires through the rubber grommets from the top—black, yellow, green, orange nearest the back of the amplifier and blue, red, purple through the holes closer to the front of the amplifier. The hardware is together in its own bag—½” #6 truss head machine screws, fiber and metal flat washers, lock washers and nuts. Be careful because the top aluminum panel can easily be scratched. I included fiber washers to go in between the transformers and the aluminum top to help protect it. This step can be tricky to get all the washers and screws in place. Put the fiber washers over the screw holes, put screws into the transformer holes and lower the transformer with screws down through the washers and holes of the top panel. Then, hold in place and lean the amplifier on its side while you put on the flat washers, lock washers, and finger-tighten the nuts on the inside. The output transformer covers have enamel paint which is a hard coating but will scratch or chip. I suggest using a nut driver from the bottom, rather than turning the screws with a screwdriver, so it doesn’t scrape as it turns. Tighten securely.



(2) output transformers

Output transformer hardware (8 each):
#6 ½” truss head screws
Fiber washer
Flat metal washer
Lock washer
Nut

Holding up your amplifier on your work space

At this point, you have several large and heavy transformers of uneven height on the amplifier, and to work on the bottom of it, you may want a steady way to hold the amplifier upside down, several inches above your work bench. You can use anything, a few small boxes or blocks, just make sure it’s secure and something that won’t scratch the surface. I built a pair of stands shown here using wood with soft padding glued to the tops. These are taller than needed for the AE1 because I use them for other amplifiers that have larger transformers.

18 Trim and wire the **output transformer leads**. For the secondary side, closest to the back of the transformer, the green lead is for 8 ohm speakers and goes to the red speaker terminal. If you want to use speakers of another impedance, you could use one of the other wires instead: yellow is for 4 ohm speakers and orange is for 16 ohm speakers. 8 ohms is the most common impedance, so I would expect most people to use this. (Trim, tie off and cover the unused leads with heat shrink tubing.) The black leads are common and go to the black terminals, but you will also wire these to ground. Trim a 3" piece of green hookup wire that will connect between the two black speaker terminals, and another 4" piece of green wire with a ring terminal soldered to the end that will go to the star ground.

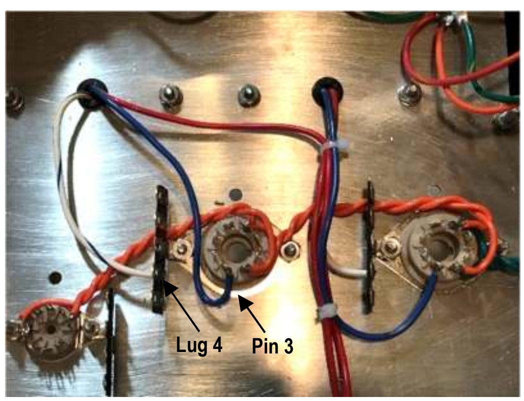
Heat shrink tubing

Nylon zip ties

Note that the binding post acts like a big heat sink and your solder may not easily flow if you try to heat up the post. Run your solder right into the iron tip and make it flow over the wires and lug tip to make the connection. Don't hold your iron on the post so long that you heat up the binding post to a high temperature—it has plastic parts that could start to melt. Check that your wires are secure after soldering.

On the primary side of the transformers, the red wires will get the B+ voltage, so need to go up near the front of the amplifier where we will have our power supply capacitors. We will trim and solder these later, for now just route them up near the 3-lug terminal strip in the front. The blue wires are the other side of the output transformer primary and will go to the anode (plate) of the output tubes. This is pin number 3. The purple wire is an ultralinear tap and will go to the screen of the tube, but this will require a resistor first, so solder the wire to the hole on the bottom of lug 4 (counting down from top) on the terminal strip next to the tube. To help route some of the wires between the tubes, use two of the zip ties.

As you connect all of these, keep the wires from the left transformer with the left tube socket and speaker terminals, and the wires from the right transformer with the right socket and terminals.



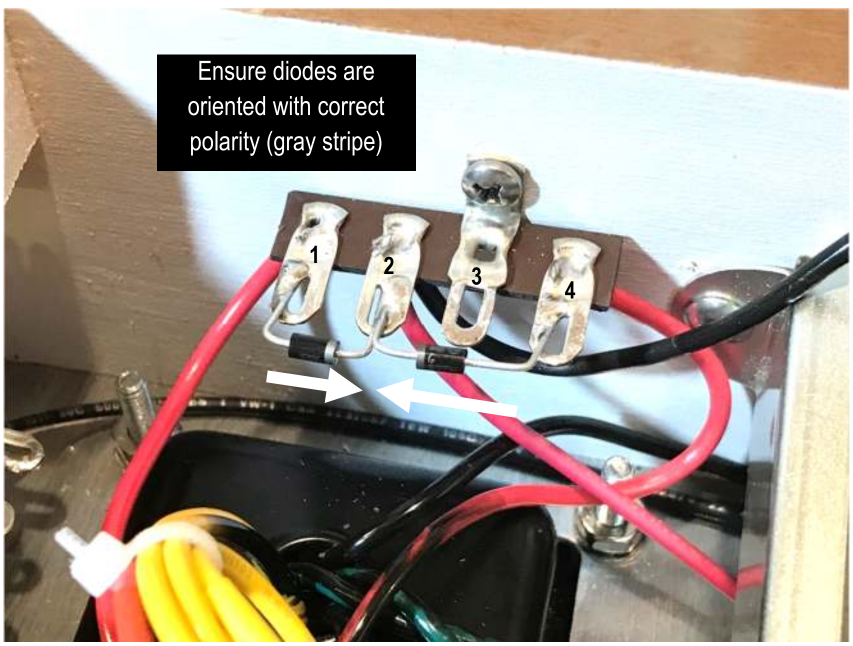
AE1-C Note
These photos are from the AE1 and show different color wires. Please follow the written instructions. Transformers for the AE1-C use black as common (instead of white), green as 8 ohm output (instead of yellow), and purple for the screen tap (instead of white/blue-stripe)

19 Ok, let's start to work a bit on the power supply. Mount the final **4-lug terminal strip** to the side of the chassis in the pre-drilled hole next to the choke using a **3/8" pan head screw**. We will use this for the diodes.

The rectifier diodes convert the power transformer secondary high voltage from AC to DC. Trim and strip the **red leads** from the power transformer to a shorter length so they reach the two end lugs (lugs 1 and 4) of the terminal strip with a bit of slack. Bring the leads up from the bottom through the holes closest to the wall of the chassis, solder & trim.

Cut a 7" length of **red hookup wire** and strip the ends. Now trim **one of the black leads from the choke** to a shorter length to reach under the terminal strip. Bring both of these wires up through the hole in lug 2 of the terminal strip, solder in place, and trim any excess.

Now you are ready to solder the **two rectifier diodes** onto the bracket from lug 1 to lug 2, and from lug 4 to lug 2 (skipping over lug 3). These take the AC from the power transformer and send the rectified DC output to the capacitor and the choke for smoothing. Diodes allow current only in one direction, so you need to <u>solder them in the correct orientation</u>. The stripe (cathode end) needs to be facing the second terminal lug. Bend the leads of the diode and trim to length to fit neatly in place. Solder, trim any excess, and inspect for a clean connection. There will be 650V AC across these exposed leads and terminal lugs, so you don't want stray wires or bits of solder anywhere (and further reason to be careful and not poke your fingers around in the amplifier when it's powered up!)



4-lug terminal strip

#6 3/8" pan head

(2) rectifier diodes

Red hookup wire

"You can waste time with your friends picking up power converters at the Toshi station when your chores are done. Now come on, get to it!"

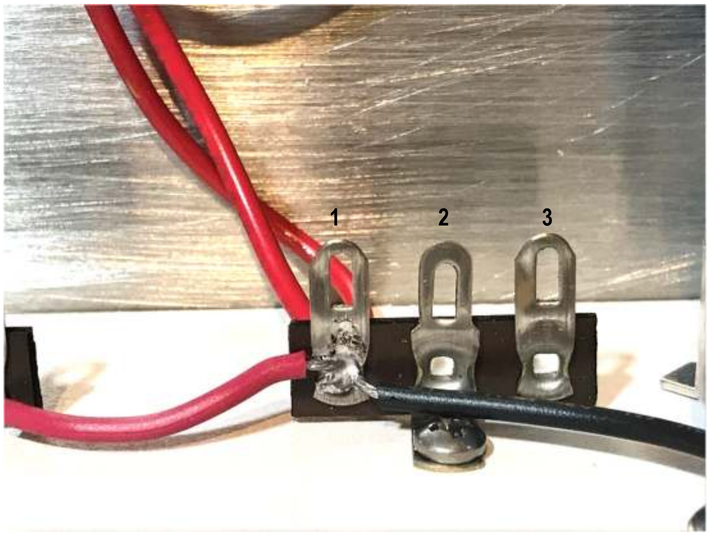
- Uncle Owen

20 Cut and strip a 1½” length of **red hookup wire**. Trim the **other black lead from the choke** to a length that reaches the 3-lug terminal strip on the front of the amplifier next to the capacitor bracket. This terminal strip will later hold another capacitor and will be a connection point for our high voltage power supply and ground.

Red hookup wire

Lug 1 (left side in photo) of the 3-lug strip will be our high voltage B+ supply point. Four wires need to come together onto this one lug (I know, seriously? Four wires? You can do this!) Take the two red wires from the output transformers, the black wire from the choke, and the small 1½” red wire you trimmed and solder them all to this lug through the hole or outer lug. In the photo below, I soldered them all into the hole, but the AE1-C output transformers have a heavy gauge wire that could be difficult to fit, and it might be easier to put one or two on the outer part of the lug. (Be aware we will later need to solder a capacitor and bleeder resistor onto this lug also.)

If you push wires down in from the top, make sure they do not have excessively long stripped ends, you won’t be able to easily trim these underneath the terminal strip afterward. Solder these all in place and check for a secure connection with no stray strands or solder blobs.



21 Install the **220uF capacitor** in the capacitor bracket. This is a polarized capacitor and it's important to wire it with the correct polarity. There is a stripe on one side indicating the lead on this side is negative; the other side is positive. Install it in the bracket so the negative side is on the left (positive closer to the choke). Tighten the bracket bolt, but do not overtighten.

220uF capacitor

Cut and strip two 3" and one 8" lengths of **green hookup wire**. Solder a **ring terminal** to one end of the 8" piece. This will go on the star ground bolt.

Ring terminal

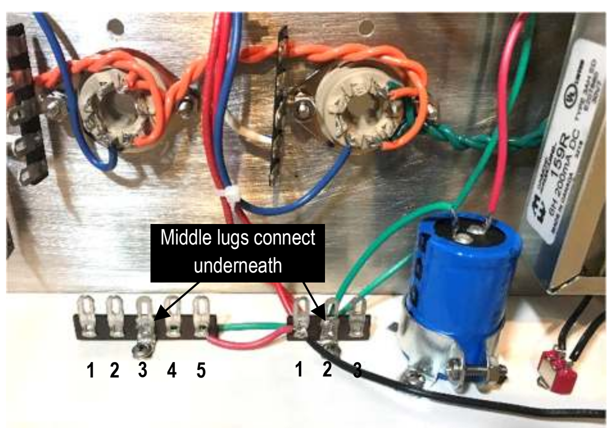
Green hookup wire

Using the 7" red wire that connects to the diodes, solder the end to the positive lead of the 220uF capacitor. Solder one of your 3" green wires to the negative side of the capacitor. The capacitor has no lug holes, so you'll need to find a way to hold the wires in steady contact while you solder them. I usually tin the leads and put a little solder on the iron tip before holding the wire in place with one hand.

22 The middle lug (lug 2) of the 3-lug strip will be our power supply ground point. We need three wires connected into this lug in the hole nearest the chassis wall: one is the 8" wire that will go to the star ground, one is the other end of the 3" green wire that connects to the capacitor, and the third is your other 3" green wire that you haven't used yet. Bring the three wire ends up through the hole from the bottom, solder neatly, and trim any excess.

Run the other end of the 3" green wire to the middle lug (lug 3) of the 5-lug strip to the left. This will connect the ground of the next filter stage. Bring up through the hole and solder.

(Do not solder the other end of the red wire yet, but the picture shows where it will eventually go.)



Inspection point

Take a look back and trace the power supply:

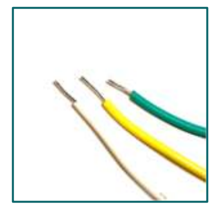
- ☐ Two red leads from high voltage secondary of power transformer go to the end lugs of your diode bracket (this will be ~650VAC)
- ☐ From there the diodes connect to the second lug, with the gray cathode stripe closest to the second lug (diodes convert to DC)
- ☐ From here, it connects through a red wire to the positive side of the 220uF capacitor (reservoir capacitance to smooth the DC peaks) and also passes into the choke through one of the black leads (inductor resists ripple current, filtering the power supply)
- ☐ Negative side of the capacitor goes to your middle lug of the 3-lug terminal strip, and from there on to the star ground
- ☐ The other black lead of the choke goes to the left side lug and this B+ voltage will then go through the red wires through the output transformer primary side (and then back through the blue wires to the power tube anodes via pin 3)
- ☐ Check all solder points. No stray solder? No stray wires needing to be trimmed? Wires routed neatly?

The power supply isn’t all in place yet. A few more capacitors and resistors, but it’s easier to access the tube sockets without these, so we’ll come back and finish this section out later.

23 In this step you will wire the **potentiometer** so you can install it. The chassis has a recessed hole for the potentiometer, which makes it difficult to solder leads onto the lugs after its mounted, so you'll do this beforehand.


Potentiometer

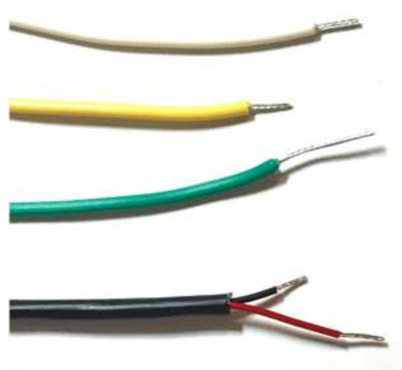

Shielded wire


White, yellow, green hookup wire

Cut a **5" length of green hookup wire**, **4" yellow**, and **6" white**. The yellow and white will be your left and right signal wires that go from the middle connectors of the potentiometer (attenuated output) to the driver tube terminal strips. These can be stripped normally. The green wire is a ground wire for the potentiometer, and we'll use the same wire for both left and right channels. Strip one end to have bare wire long enough to connect across both the front and back connectors on the potentiometer.

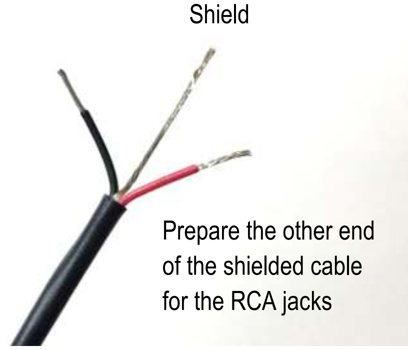
You also need to strip and prepare the **shielded input signal cable**. This is a two-conductor cable that will carry both channel signals from the RCA input jacks to the potentiometer. You will need to very carefully cut about ¾" of the outer casing off each end, without cutting into the interior wires. It takes very little pressure to cut the casing, and by wiggling it back and forth, it will easily break free. It's easy to trim too deeply and cut into the interior wires—go lightly! The kit includes a 14" length, but you probably only need about 12", just in case you accidentally need to try again—I got your back.

Prepare wires for the potentiometer



There is a black and red signal wire inside, and a bare stranded shield that can be twisted into a wire. You will ground this shield only on one end, nearest the input jacks (to avoid creating a ground loop). The end of the shielded cable that is wired to the potentiometer requires only the black and red leads, so cut off the bare shield wire here. The red and black leads will go to the two gangs of the potentiometer, so one lead needs to be longer than the other. Trim and strip so the red wire reaches longer than the black one to be soldered to the connector closer to the knob post.

The other end of the shielded wire will go to the RCA input jacks. Strip as shown in the picture and hold up temporarily to see that they can line up to fit the two jacks. You'll need the shield wire on this end, so don't cut it off!



Prepare the other end of the shielded cable for the RCA jacks

It's important to wire up the potentiometer correctly so that it will attenuate the channel signals in the expected way. Note the picture here with knob shaft oriented to the left, wire the input signals to the top connectors, output wires to the middle connectors, and ground soldered to both bottom connectors. Make sure the wires don't touch each other.

The AE1-C comes with an Alps potentiometer that is very good quality, but the connectors are pins, not lugs with holes, so it's a bit tricky to solder to them. I suggest you hold the potentiometer securely using a helping hand tool or other method and then put a bit of solder on your iron tip, then hold each wire in place and solder. I know you can do it! If your wire moves, try again. You don't want a cold solder joint.

Finally, mount the potentiometer in the chassis. A small alignment tab fits into a pre-drilled hole so it mounts flat and oriented with wires facing up as you work on the amplifier upside down. Use the flat washer and nut to carefully tighten in place from the outside.

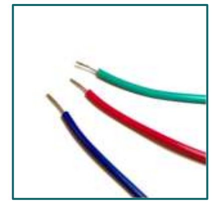
Shielding the input signal

The input signal is a sensitive part of the circuit, carrying our precious audio that will be amplified. A metal shielding inside this cable is run to ground on one end to protect the signal wires from picking up noise or interference from the surrounding amplifier or room environment. We want to maximize our efforts to keep noise and hum out of the amplifier. It should be almost dead silent when you are done, assuming good electrical environment in your house, and you don't live next door to a radio tower.

We aren't shielding the white and yellow leads going from potentiometer to tube socket because they are short lengths and it becomes inconvenient to try and shield everything. Skeptics may also question carrying both signals in this two-conductor cable, risking some level of cross-talk between the channels. I've used this method multiple times without any issue. Some cross-talk will exist in this amplifier, but it's due to having both channels pre-amplified using a dual-triode tube and is not likely to be noticeable.

24 Ok, I'll be honest: boring step here, but important to get right. Put on some *Yes, Owner of a Lonely Heart*, and let's run a few connector wires. Trim and prepare these:

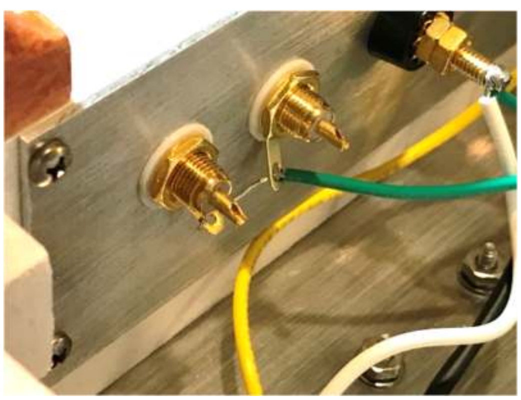
- 4" and 5½" red – to run the B+ power from power supply to each channel of the driver tube socket
- 3" green – for an interconnecting ground wire on the driver tube socket
- 4", 7", 7", and 9" green with ring terminal on one end of each – for running to ground from the driver tube, power tubes, and input jacks
- 3" and 5½" blue – to carry the signal from each channel of the driver tube to the power tubes



Blue, red, green hookup wire

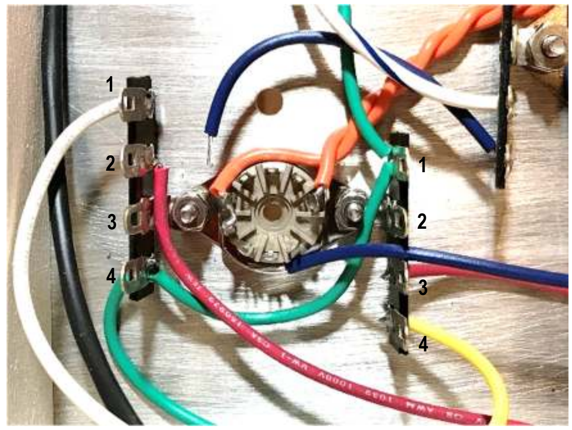
(4) Ring terminals

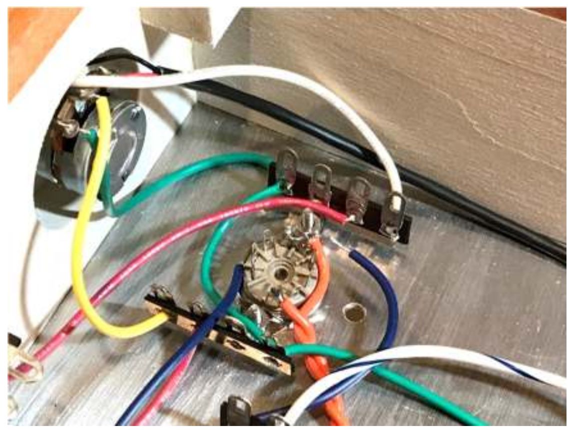
Let's start with the RCA input jacks. Use one of the 7" green wires with a ring terminal on one end. Strip the other end with an extra-long exposed wire and run it through both of the RCA jack outer lugs. We'll just use one ground wire for both channels. Then put in place the shielded cable you prepared in the previous step. Put the shield wire through one of the outer lugs, and the black and red wires to the respective inner connectors. Solder all in place. See what's happening here? We ground the common (outer) wires of the input, ground one end of the cable shield, and run the audio signals to the potentiometer.

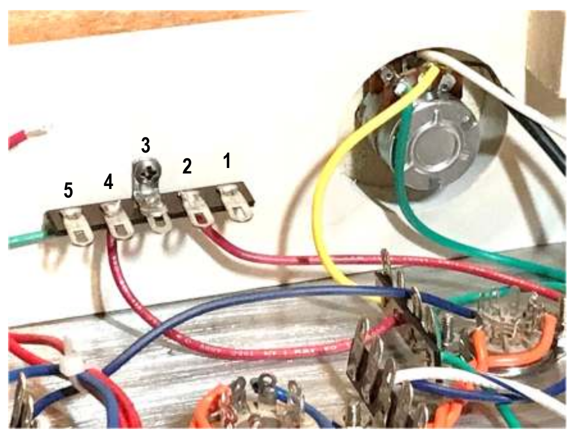


Next, run the other wires from the potentiometer to the 9-pin driver tube socket. White goes to lug 1 on the left-hand terminal strip (see photo for numbers), yellow to lug 4 of the right-hand strip. (Wires in this entire step should use the round holes on the bottom of the lugs, nearest the aluminum chassis. Leave the bigger top lug openings for components that will be added later.) These white and yellow wires are the audio signal that eventually goes to each grid in the dual-triode tube. You can trim these wires a bit to get them as short as possible without making too tight of a connection. Dog-leash length, not dental floss tightness, if you know what I mean. Trim any excess, so you don't have leads poking out.

The ground wire from the potentiometer needs to go to lug 4 on the left-hand terminal strip, but at the same time and in the same hole, solder the 3” green wire, so both wires are connected in place. This short green wire is routed around the tube socket to lug 1 on the right-hand strip, and again at the same time solder the 9” green wire with the ring terminal on the other end. The ring terminal goes to the star ground bolt. Getting comfortable with this dual-wire soldering stuff? Good, because it gets a little harder later.





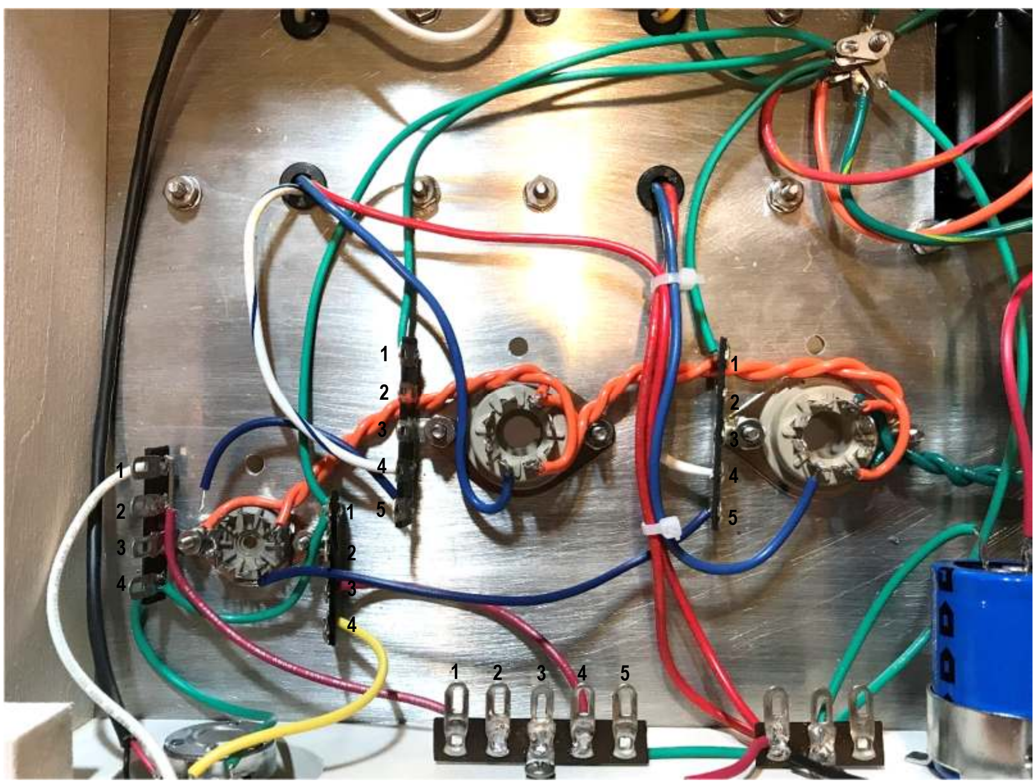


Run the 5½” red wire from lug 2 on the left terminal strip of the tube socket to lug 2 on the 5-lug power supply terminal strip on the front of the amplifier. And run the 4” red wire from lug 3 of the right terminal strip on the tube socket to lug 4 of the 5-lug power supply strip. Again, these are all using the round holes closer to the chassis walls, not the larger outer parts of the terminal lugs that later will get some resistors and capacitors. On the power supply terminal strip, run these red wires up from the bottom so they are neatly out of the way. Trim the leads of these after soldering, so you don’t have a risk of high voltage touching something else.

Almost done. The blue wires will connect the driver tube to the power tubes. But we won’t yet solder these to the 9-pin driver tube socket because it needs to be done at the same time as a load resistor, but you can lay it out roughly where it will go. Put the 3” blue wire near pin 6 of the driver tube and solder only the other end to the fifth lug hole of the terminal strip on the left-hand output tube socket. Put the 5 ½” blue wire near pin 1 of the driver tube and solder the other end to the hole in lug 5 of the terminal strip on the right-hand output tube socket. Notice in the photo how I routed these wires.

Finally, solder a 7” green wire to lug 1 of the terminal strip on the left-hand output tube socket, and solder the 4” green wire from lug 1 of the terminal strip on the right-hand output tube socket. The ring terminals on the other end of these wires goes to…yah, you got it, the star ground bolt.

Check all of the photos here and the layout diagram in the appendix to ensure you have these wires all in the correct places. Ok, now check it again to make sure. Zoom on in there and take a good look. That guy in the *Owner of a Lonely Heart* video was having a hard time with stuff, wasn’t he? I’m pretty sure he didn’t check his tube socket wiring well enough and guys were after him for it.



25 Now for my favorite part. I just love resistors and capacitors, don't you? Let's put some of those little guys on the 8-pin output tube sockets.

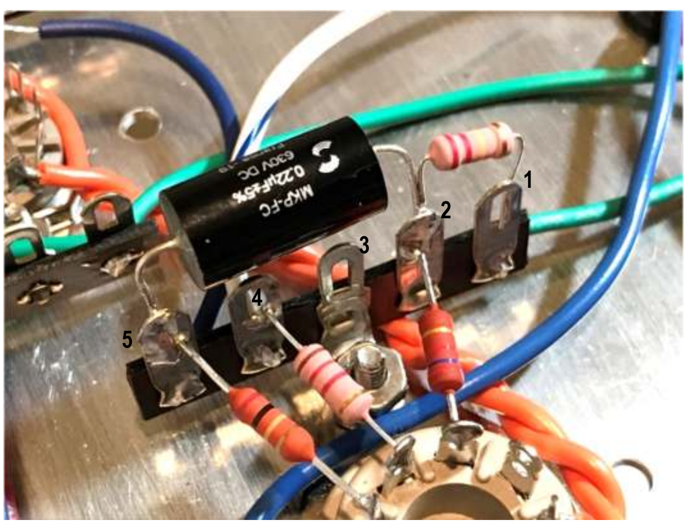
It's easy to get resistors mixed up. They're little, with colored stripes like those candies your aunt had in a jar just as a decoration, and you might set one down for a moment, and then—wait, was that the 2.7k or the 180k? So get out your multimeter, and check every one of these before you solder it in place just to make sure you've got the right one. Use the layout diagram to double-check locations.

Here we go. Let's do a few cupcakes first for practice. The **100 ohm resistors** go between the ultra-linear tap and the screen of the tube, like a grid-stopper to help with stability. Trim the leads of this resistor and solder from lug 4 (where the purple wire is) to socket pin 4. Beautiful. Do the other tube, too. See the callout box on the next page for a few tips.

Some steps will require soldering more than one component to the same lugs. Trim and shape each one to fit the space where it goes, and then by systemically going in order and soldering one side first, you can get each component to hold in place as you add more.

- **180k ohm** feedback resistor from socket pin 3 (blue wire also here) to terminal strip lug 5
- **Coupling capacitor** from lug 5 to lug 2
- **2.7k** grid stopper resistor from lug 2 to pin 5 of the tube socket
- **220k** grid leak resistor from lug 2 to lug 1

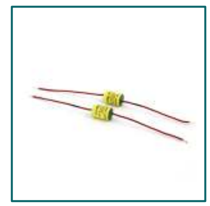
Do both tube sockets. And special request: save a few of spare lead clippings for use in the next step.



AE1-C note: Photos show components from the AE1 kit so some components and wires will look different. The AE1-C coupling capacitors use stranded leads instead of solid. This makes them flexible, and you need to trim to a shorter length, but don't trim too short—it's ok if it's standing off from the strip a bit.

(2) 100 ohm resistors

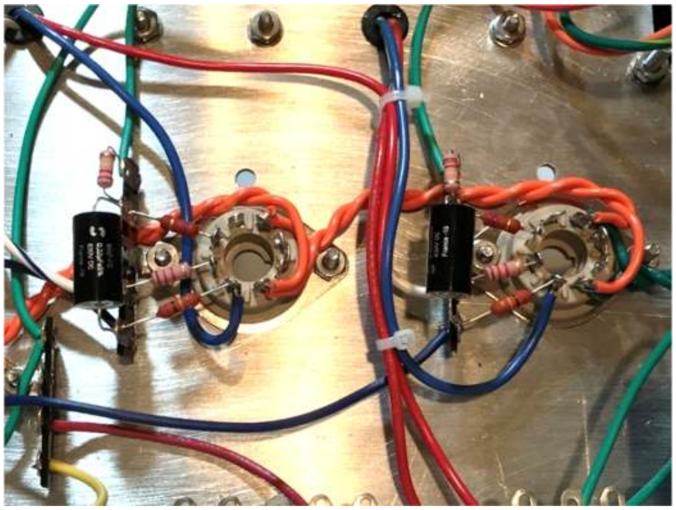
(2) 180k resistors



(2) 0.22uF coupling capacitors

(2) 2.7k resistors

(2) 220k resistors



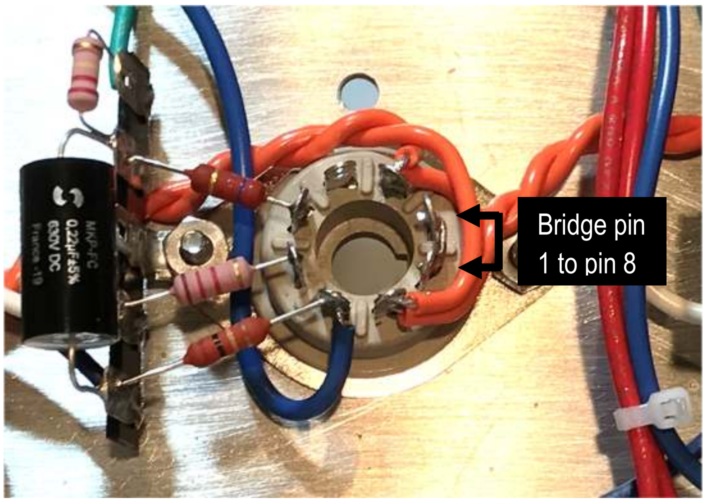
Point-to-point soldering

Some people are masters of neat and tidy point-to-point soldering—perfect straight angles, flawless lead shaping, impeccable solder joints. The first few amplifiers I built, mine looked terrible—wiggly leads and crooked components all over the place. We're all on a journey, right? Maybe you are already awesome, but if not, just give it your best. Keep leads relatively short, nothing touching other things, no loose joints or big solder blobs or excess leads poking out.

I like to trim and shape the leads with needle-nose pliers and test-fit a few at a time to see how they will fit next to each other. A little bend on the end can ensure it's got a good physical connection. Sometimes I'll put a little solder on the tip of my iron, hold the component with one hand and tack one side to get it to hold steady. Then I can use both hands to solder the other side and go back and neaten up the first one. It's important that the component doesn't move while the solder cools and hardens; if it moves you end up with a "cold solder" joint which may not be a good enough connection. Inspect each one after soldering to ensure it's a solid joint. Always trim your leads afterward and pick up the clippings.

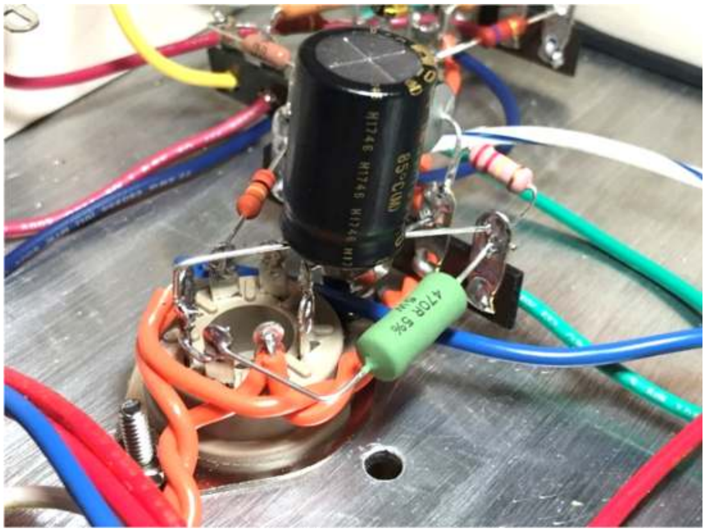
26 Little special step here. We're going to connect pin 1 to pin 8 of the octal tubes. The EL34 is a pentode, and it has a suppressor screen to prevent those doggone electrons from bouncing off the plate and floating back to the screen. We want the voltage on the suppressor to be low, and the simplest method is to tie it to the same voltage as the cathode.

Using a bit of a spare lead clipping you saved from the last step, make a little U-shape that can neatly fit from pin 1 to pin 8 in the bottom hole closest to the socket, and solder in place. Similar to what you did in step 16.



27 We'll finish out the output tube sockets. We need the **5W 500 ohm cathode bias resistor** to run from the tube cathode on pin 8 to the ground lug (lug 1) on the terminal strip.

At the same time, we need the **220uF 50V cathode bypass capacitor** also running between the same points. This allows AC voltage to go to ground, while the bias resistor holds the cathode at a steady DC voltage. Since we tied pin 1 and pin 8 together, we have a convenient second hole to use, so run the capacitor from pin 1 to the ground lug. This is a polarized capacitor, so ensure that the lead on the side with the negative stripe is going to ground. Solder these in place. (Note the photo here shows a 470 Ohm resistor from the AE1, but the AE1-C uses 500 Ohms).



(2) 500 ohm 5W resistors

(2) 220uF 50V capacitors

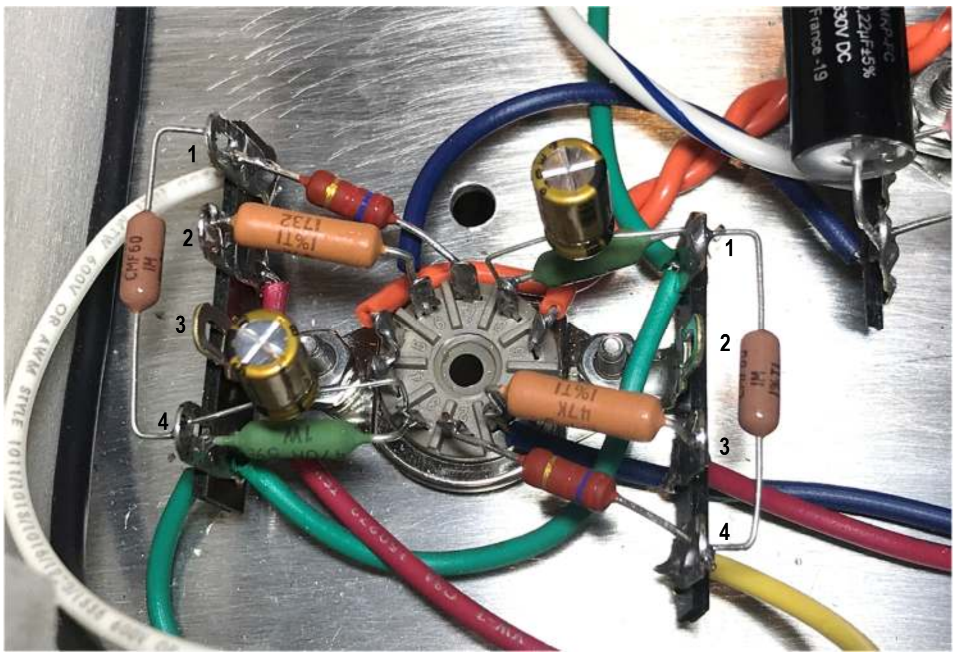
Keeping cool

You'll note how I shaped the cathode resistor to be off to one side. Try to give this resistor some air-space around it; it will dissipate almost 2 watts of power, which creates heat. You don't want this near your capacitor or too close to the nearby wires (my photo gives an illusion that the resistor is touching the blue wire, but there's a gap in space). Even the leads should not touch other wire insulation because they can heat up. The hole in the chassis allows some airflow to pass up and out. It's not really necessary because this amplifier has plenty of interior space and most of the heat comes from the tubes and power transformer which are outside the chassis, but we still want things as cool as possible. I have measured the interior temperature after operating the amplifier for a while, and it was well below component ratings.

28 Well done so far. It's time for the hardest part of the build—the 9-pin driver tube socket. This is a dual triode in a small size, so there are a lot of components that all need to go around a small physical space. Take your time, shape your components carefully, and you'll have no problem! Here's what you need, in the order I suggest. Remember to use your multi-meter to double-check you are putting the right resistors in the right spots.

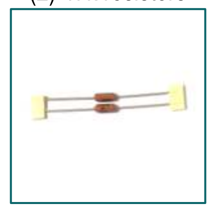
- 1k grid stopper resistor from left terminal lug 1 to pin 7 (white input signal)
- 47k anode load resistor <u>and</u> blue signal wire on pin 6 to left terminal lug 2 (high voltage B+)
- 1k grid stopper resistor from right terminal lug 4 to pin 2 (yellow input signal)
- 47k anode load resistor <u>and</u> blue signal wire on pin 1 to right terminal lug 3 (high voltage B+)
- 1M grid leak resistor on left terminal lug 1 to lug 4
- 470 ohm cathode bias resistor from pin 3 to left terminal lug 4, AND 100uF 25V bypass capacitor on these same points (negative side to lug 4)
- 1M grid leak resistor on right terminal lug 1 to lug 4
- 470 ohm cathode bias resistor from pin 8 to right terminal lug 1, AND 100uF 25V bypass capacitor on these same points (negative side to lug 1)

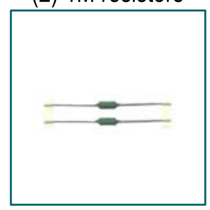
Boom. Good job. You are a Rockstar. Inspect & trim any excess leads.

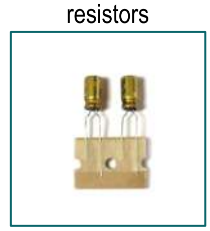



(2) 1k resistors


(2) 47k resistors


(2) 1M resistors


(2) 470 ohm resistors


(2) 100uF 25V capacitors

Note: astute builders who know resistor color codes will notice that this photo shows a 2.7k grid stopper instead of 1k. I previously was using a larger grid stopper but have revised the design; I believe 1k is sufficient here.

Inspection point

Take a moment to inspect all the tube sockets and use the schematic and layout diagram to review:

- ☐ Trace all the wires that should be connecting to the tube sockets and ensure they are on the right pins, and clean/secure solder joints:
  - Ground wires?
  - Signal wires?
  - Output transformer wires?
  - B+ voltage?
- ☐ Double-check you have all the resistors and capacitors in the right places:
  - Output tubes: coupling capacitor, grid stopper, grid leak, feedback resistor, cathode bias resistor & bypass capacitor
  - Driver tube: grid stopper, anode load, grid leak, cathode bias resistor and bypass capacitor
- ☐ All your leads trimmed, not touching anything?
- ☐ No big solder blobs needing to be cleaned up?
- ☐ You are having a good time and your spouse or partner isn't too annoyed at how much time you are spending in the basement? Go hang out with your kids if now's a good time, OR, go get a snack.

29 On the home stretch here! Let's finish out the power supply filtering. We saved it until now so we'd have better access to the tube sockets (a few of these capacitors will stick their big heads out into space).

56uF capacitor

Solder the **56uF 500V capacitor** on the 3-lug terminal strip with the positive on lug 1 and negative on lug 2. Also solder the **220k ohm bleeder resistor** on these same two lugs. This will cost us a few mA of current during operation, but has the benefit of ensuring the energy leaves the capacitors when you turn off the amplifier, as a safety measure. With no bleeder method, your capacitors could store energy for a long time, and there's a risk you'd turn off the amplifier, unplug it, thinking it's all safe, but if you touched the wrong spots—POW! Know what I mean? Don't skip this step.

220k resistor

I know, there are a lot of connections on lug 1. Everything clean and well-soldered?

30 The driver stage gets an extra filter and decoupling using a resistor and capacitor for each channel. On the 5-lug terminal strip, run the B+ from lug 5 to lug 1 using a **2" red hookup wire** while also soldering to lug 5 the red B+ supply wire coming over from lug 1 on the 3-lug strip.

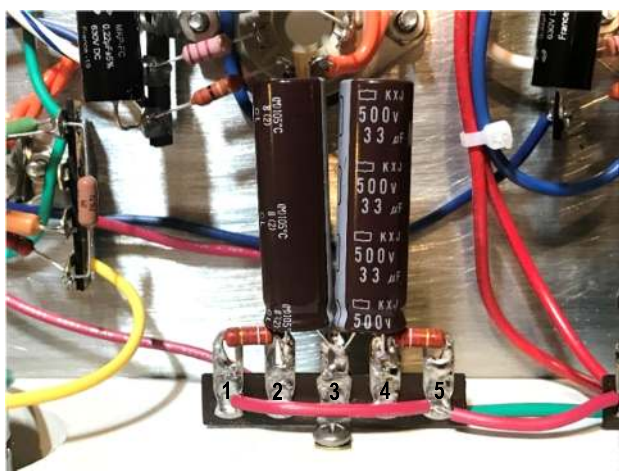
(2) 33uF capacitors

Position the two **33uF 500V capacitors** so that lugs 2 and 4 have the positive leads, and lug 3 (ground) has the negative of both. Trim the leads to an appropriate length and solder the negative leads to the lug.

(2) 3.3k resistors

Then, use two **3.3k ohm resistors** from lug 1 to lug 2, and lug 5 to lug 4. Trim leads, solder in place, along with the positive sides of the capacitors.

Make sure there are no long leads poking through down below this terminal strip.

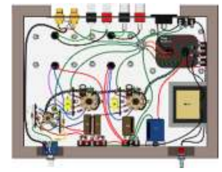


Love. Nice job.

Final check point

You are very close! Before final steps to lock down your ground point and close up the amplifier, it's time for a double-check of all your work. Use the layout diagram in the appendix and trace through every single wire and component. You can also go back over all the steps to re-read if necessary. There are a lot of steps, and anyone can make mistakes. Now is the best time to find them, rather than after you turn on the power and something goes wrong and causes damage to a component. At minimum, follow this checklist:

- ☐ Trace the circuit of your mains voltage coming from the power inlet, through the thermistor and power switch and closing a loop with the primary (black) wires of the power transformer.
- ☐ Use a multimeter to confirm that you wired the power switch properly: no continuity between leads in the off position; continuity in the on position. (No power cord connected.)
- ☐ Check the heater wiring coming out of the power transformer and going in parallel to correct pins on each tube socket, with wires neat and not touching other things
- ☐ Check the wiring of the power supply, including high voltage secondary wires from the power transformer, diodes, capacitors and choke.
- ☐ Verify the diodes are oriented with correct polarity, and all electrolytic capacitors oriented with correct polarity.
- ☐ Check the output transformer wiring all going to the correct places and no mix-up between which ones go to the left channel and which to the right.
- ☐ Check that tube sockets are oriented with the correct pin numbers, and components or wires to those pins are correct
- ☐ Verify 11 wires going to the star ground point from where they should, including the center taps of the power transformer for high voltage and for heater voltage.
- ☐ Use your finger to press on all solder connections and components to ensure solid connections.
- ☐ Check that you have tightened down the transformers, power switch, potentiometer, RCA jacks and speaker jacks so that none are loose
- ☐ Check that no wires are touching the 5W cathode resistors on the power tube sockets, and no wires are touching the thermistor. These will heat up.
- ☐ Check that all leads are trimmed short. Verify there are no stray strands of wire or anything touching the aluminum top and back panels or leads of other components or tube sockets.
- ☐ Turn the amplifier to the side or upside down and ensure no loose wire clippings are rattling around. Find them and remove.
- ☐ Use a multimeter to touch anywhere on the aluminum top and back panels to verify continuity to the earth ground on the IEC inlet (middle prong)
- ☐ If you are unsure about anything, re-read. Send an e-mail or check online if you have questions. If your spider-sense is tingling, it's worth checking on it!
- ☐ Tell yourself how great you are!

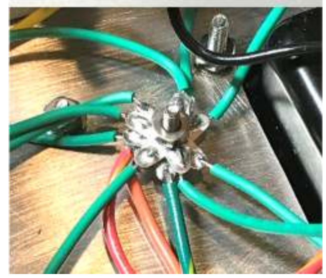


Use layout diagram in appendix

Another option I suggest is to review the schematic and read through **Part II** which explains how the circuit works. That lets you look at your amplifier and understand the logic of the wires and components and where they are (or should be).

31 We will see success momentarily!

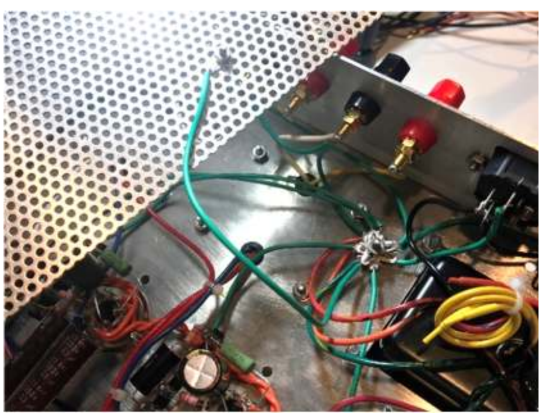
The **perforated aluminum bottom panel** of the amplifier will allow for cooling airflow while protecting you and others from dangerous voltages inside. For safety, we will ground this panel, just in case an internal component or wire were to ever be in contact with it.



Cut 8**"** of **green wire**, with ring terminals soldered to both ends. Put one end onto the star ground bolt.

Important step! Put on the final **lock washer and nut** on the ground bolt that you saved from step 3. Arrange all 12 ring terminals in a friendly druid circle like they are casting a spell to bless the woodland creatures and tighten that guy up. This finalizes your star ground point.

Position the perforated panel in place temporarily. A few holes have been widened and align with pre-drilled holes on the chassis. Choose any perforated hole in the area near the star ground and use the #4 3/8" machine screw with lock washer and nut to secure the other end of your grounding wire to the panel. Double-check that there are no wires touching any components that will heat up (thermistor and resistors). Then, position the bottom panel in place, and secure with four **#6 3/8" truss head screws** into the pre-drilled holes.



Perforated aluminum bottom

(2) Ring terminals

Green hookup wire

#6 nut, lock washer

#4 3/8" screw, lock washer, nut

(4) #6 3/8" truss head screws

32 Yeah, you almost forgot about the **volume knob,** didn't you? Rotate the potentiometer to one extreme or the other so you can position the knob at the right place to reflect where you'd expect to have zero volume or full volume. Place the knob on the potentiometer post, ensure it's not rubbing against the chassis, and tighten the set screw using a tiny screwdriver or allen wrench. Give it a test spin and pretend like when you had your stereo at mid-volume playing AC/DC, then Mom yelled up to your room, "Turn that down!" and then you cranked it all the way up! Heh.

Volume knob

33 I included a high voltage warning sticker to place on the bottom of the amplifier. I know you already know, but just as safety for some future unknown person who might get this amplifier. (I know, you think I'm overdoing it, but I just want people safe, ok?)

Also, the amplifier chassis has the Analog Ethos "AE" logo on the front. I used a removable decal for this, in case you prefer to not have this on your amplifier. You can carefully peel it off to leave the front blank.

Place warning sticker on bottom of amplifier

Logos & branding

Visual logos on any product can either enhance or detract from the design. I have intentionally avoided buying some products because they manufactured it with the brand logo too prominent and I felt it would distract from my intended design use. In this case, the amplifier is a holistic kit and I thought the AE logo is an appropriate identifier and brings some visual balance and completeness to the front of the amplifier, but if you don't think so, feel free to remove it! Put your own initials there if you like, you built this!

34 Last steps and **power up** time!

Install the **2A fuse** into the fuse tray of the IEC power inlet. Kinda hard to open that little tray and get your fingers in there, I know.

Insert the **12AT7 tube** into the 9 pin tube socket. The pins will only align in one orientation. Insert the two **EL34 tubes** into the tube sockets. There is an alignment notch on the center pin so it fits in the right orientation. All tubes should be down securely in place with no gap underneath.

Plug in a line level audio input signal to the RCA jacks. This could be a CD player, output from a mobile device, DAC, a source from a preamplifier, etc. You will need your own RCA interconnect cables.

Test source & speakers

I typically use dummy loads or crappy speakers that I got at a thrift store for $5 for testing until I know things work. And I use an old unused cellphone that plays some music as my source. Then after I know things are working properly, I move to my good speakers and source equipment for listening. It's up to you what you decide to connect, but I would not recommend wiring up expensive speakers and equipment for your first test.

Connect 8 ohm speakers (or other impedance if you used one of the other transformer taps) to the speaker binding posts. Do not run the amplifier without speakers connected (or equivalent dummy load resistor rated 10 watts or more).

Ensure the power switch is in the off position and plug in the **AC power cord**. Plug into the wall or safe power strip.

Now… I suggest you queue up a first-try song. I like *Diana Krall, S'Wonderful*, because, yeah, it's wonderful that you did this, right? Pick your own, though, whatever you like. Ozzy. Beatles. Abba. You know, whatever.

With the volume at about ¼ to ½ and an input signal on, turn on the amplifier. You should see the tube filaments start to glow, and sound start to come up after 5-10 seconds. Watch for these things and turn it off immediately if you notice any:

- Strange and unexpected sounds
- Sparks, smoke or strong burning smells. (Some heat smells are normal as the tubes and components get to operating temperatures.)

2A slow-blow fuse

AC power cord

12AT7 Tube

(2) EL34 Tubes

Now celebrate! This is the time when you smile. You did it, and should be proud of yourself, right? A bunch of resistors, capacitors, transformers, and tubes, and you get this beautiful music coming out. How cool is that? Tell your friends you built your own amplifier. Turn it up. Get a gin & tonic to celebrate and chill for a while. **You. Are. Awesome!**

Gin & Tonic (not included with kit)

A few quick notes on operating your amplifier:

- The tubes will get very hot in a few seconds, and the power transformer will get hot over a longer time period (maybe an hour or more). This is normal. Obviously you don't want to touch them or allow other things to be close to them. See the safety precautions on page 2.
- Remember it is not a high-power amplifier, so you may need to turn up the volume knob near the max to get to loud listening levels, depending on your source signal level. It's all cool, turn that baby up if you need to. But if you are using a pre-amplifier, don't overdrive the amp. If it sounds distorted, turn it down!
- Always turn off your amplifier when not in use. This is a Class A amplifier, so it is always drawing power. It's not only a waste of electricity, but it could wear out your tubes prematurely and has risks if you leave a very hot amplifier running for hours unattended.
- When others are in your home and look at your amplifier questioningly, just slip another album out of its cover, take a sip of your Manhattan and say, "Yeah, it's a tube amplifier that I built myself." They may not understand, but that's cool. You can read Part II and tell them how a tube works.

Trouble-shooting

☹ It didn't work? Aw man. Here are a few things to check:

- Power connection / power strip all ok and definitely providing power?
- You put the fuse in, right? Did it blow? Take it out and see if there's continuity. If the fuse blew, unplug the amplifier and review your circuit entirely again. There may have been a short somewhere that caused heavy current; see if you can find it and re-wire. I gave you a second fuse in case you need it, but don't just put it in and try again. You need to check the entire circuit to see what was wired wrong.
- Speakers are connected properly?
- Tubes are installed fully?
- Input signal is actually being generated at expected line level voltage? (Input cannot be a turntable unless you are using a pre-amplifier with a phono stage)
- Unplug, open the amplifier, and trace back over all the elements of the schematic and assembly diagram. All looks right?
- The colored wires of the power transformer and output transformers are wired to the correct places?
- None of your polarized capacitors are wired in reverse? Your diodes are not wired in reverse?
- Your solder joints are secure, with no shorts, loose leads, etc?
- Power switch seems to have continuity when on? (test this with a multimeter when unplugged, not a live circuit)
- Volume potentiometer is wired properly, and signal coming out of it and going to the driver tube socket? You can test this with the amplifier unplugged if you can run a test sine wave signal and put an AC multimeter on the tube input.
- Ground bolt—all the ring terminals connected and tightened properly?
- When turned on, do you see filaments glowing in the tubes? If not, tube wiring is all done right?

I am not providing any live-amplifier troubleshooting tips in these instructions. It is critical that you understand safety and testing techniques before you attempt to diagnose problems with a live circuit, and I can't describe all of that here or be certain if builders of the kit have this type of expertise and safety awareness. You should be experienced and comfortable with trouble-shooting a high voltage electrical device to do it—breaking down the problem by testing that you have voltage from the transformer, that it's rectified to DC, that your tubes are getting voltage to the filaments and B+ power on their anodes, that you have a correct bias voltage and current you can monitor across the cathode resistors, and many other steps. Consult someone who has this experience or background training if you have gone through the basic bullets above and still need help getting it to work. The schematic in the appendix does include typical operating voltages at key points.

Never probe around in an operating amplifier if you are unfamiliar with the safety risks or what to look for!

Also, it is possible but unlikely that a tube or other component is bad. This shouldn't be your first assumption of what's wrong. I have used very reputable suppliers and high quality components. It is most likely something in your physical circuit build. I will of course be very happy to replace any component that is not working properly. Please contact me via the website and we'll work it out.

Also, if you made a mistake and have damaged a minor component through your assembly or improper wiring, such as a resistor or capacitor, just let me know and we can work out options to get a replacement.

If you are still having trouble, send an e-mail or check the website as I may have other information posted online, and we'll see what we can do to help troubleshoot the issue. I want you to get this working, but at the same time, please know that I'm not there in person, safety is a top priority, and I may not be able to help in all cases.

This concludes the build section. The next section explains how this single-ended tube amplifier works, so you can learn in detail what is happening inside the tubes and throughout the circuit. I hope you'll read on, because this is the most empowering part of this kit—understanding how it works so you can do even more in the future!

Part II: Single-Ended Tube Amplifier Explained

To make this manual stand alone as best as possible, and to fit the bill of a complete kit—not only inclusive of the parts and assembly instructions necessary for a working amplifier, but to fulfill the learning objective of understanding how the parts and circuit work—this section will touch on some core concepts and then attempt a clear and simple explanation of the circuit. It's so fun to learn new things, you will love it!

I will not attempt to provide a comprehensive explanation of all the physics, electronics theory and math equations that would make a more robust reference. I'm not best suited to do this, and there are excellent resources online or in books (some noted in the appendix) that can teach the theory better and more extensively than I can, and much broader than this one type of single-ended tube circuit you are building. This is intended for a non-technical audience, but I will assume that you have basic knowledge of electric circuits and components such as resistors and capacitors. If you already have a strong knowledge of the theory and function of a triode or pentode vacuum tube and amplifier circuit, you may have bought this kit without a learning objective, and this section may not be necessary for you. But if you want a better understanding of how tubes and this circuit works, read on!

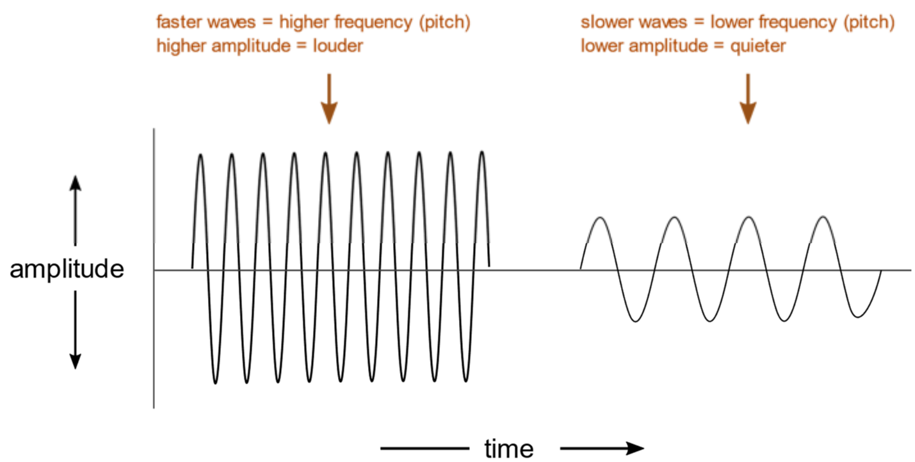
Mullard brand tubes have a long history, originally founded in England. There are relatively few manufacturers of vacuum tubes around the world now, mostly in Russia, China, and Czech Republic and Slovakia. The Mullard brand was later acquired and new production is in Russia.

Core Concepts

What is sound?

Sound is a type of energy created by vibrations. When things collide or vibrate, there is a physical process that moves the air around those things, and sound travels through the air as pressure waves that compress and expand based on the vibration source. Eventually, these sound waves reach and vibrate within our ears, creating signals that our brain interprets as music, speech, or other noises.

This barely describes the phenomenon, but a key takeaway is that sound waves can be caused by vibrations that go fast (high pitch) or slow (low pitch), and that move a small amount (quiet) or a lot (loud). We can describe very basic sound waves using these characteristics—**frequency** and **amplitude**—and plot them on a chart.

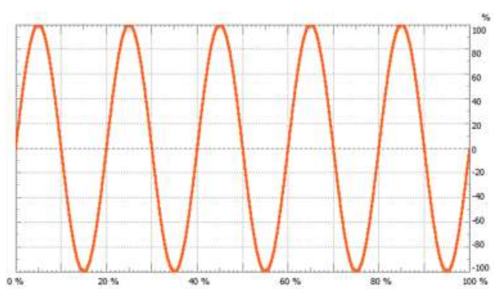


Electronic audio recording equipment converts actual sound waves moving through the air into electric signals using a microphone that reacts to the sound waves creating a voltage at a frequency and level corresponding to the sound. A recording device can capture this stream of varying voltage information, representing the sound waves, saving it for later. A playback device can take the stored information, convert it to a voltage signal again, which is then amplified to a larger, more powerful signal. We then need a device to turn it back into sound waves in the air. This is the loudspeaker, often made using a cone that is vibrated magnetically and this physically moves the air to generate sound waves that a listener can hear. There is much more to this entire process and the physics of loudspeakers, but the important concept is to understand that an audio signal in our amplifier will be a **voltage changing over time.**

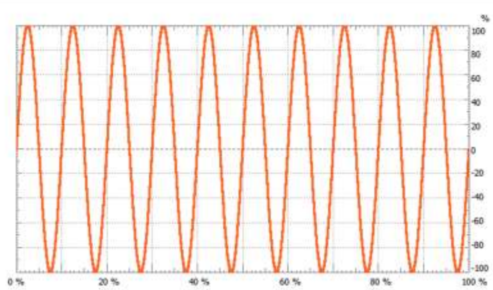
We have two ears that can each hear sound waves separately and interpret spacial location from them, and stereo recordings have two separate signals that are recorded or engineered, and eventually played back, one for each speaker to recreate a form of dimensional soundstage. In most cases through this manual, we will discuss a single process of audio amplification, but know that this process is duplicated, one for each **channel** (left and right).

Pure cycles of rising and falling amplitude over time are **sine waves** and can be described with math formulas that I won't introduce here. But you could think about sine waves as a type of building block that, in complex combinations of frequency, duration and amplitude, can make up music or other audible sound. Combinations of multiple waves will add to a compound wave, as shown in a simple example below. This will be important when we start to discuss distortion and harmonics.

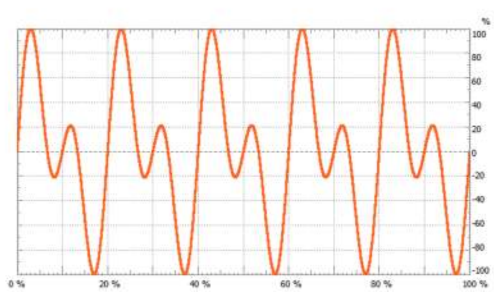
80 Hz sine wave



160 Hz sine wave



resultant waveform when combined

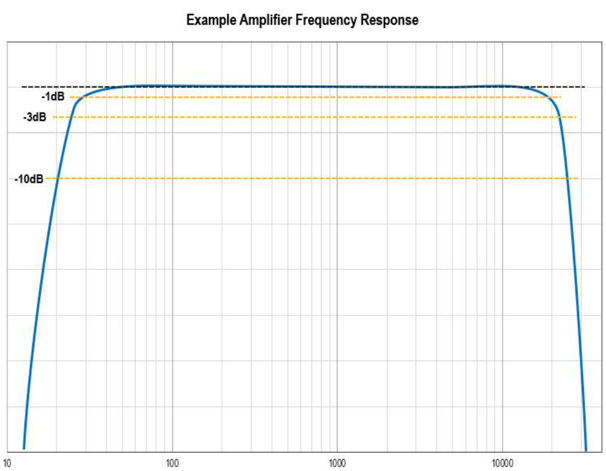


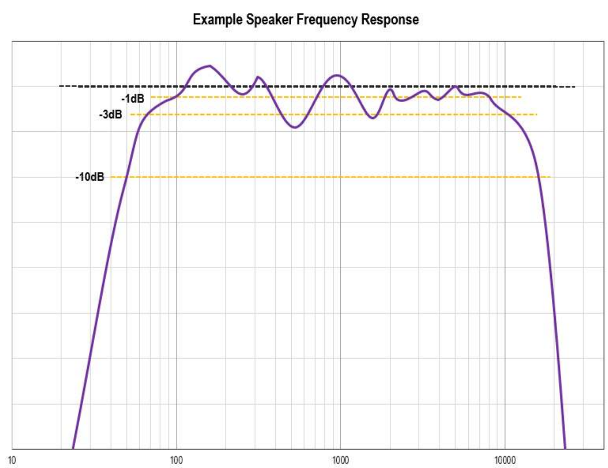
Analog vs. Digital

I will take a moment to point out that this entire process of generating, transmitting and hearing sound is **analog**—continuously variable movement and interpretation of sound waves. And the process of recording and playback is also analog using a continuous signal voltage. Conversion of the signal to digital information and then later back to analog is commonly used now in recording and playback, and can be done with sophisticated hardware and software to preserve the original analog information as closely as possible, but the natural physics of sound is of course not digital. I'm not a purist, and I use digital music streaming among other devices, both digital and analog. But there is a fascinating beauty and pleasure in learning and understanding the physics and electronics of analog music playback using tube amplifiers and passive loudspeakers (and perhaps other analog devices you use, such as magnetic tape or vinyl).

Humans can hear sound only within certain frequencies. To cover human hearing adequately, most audio equipment is designed or evaluated in the range between 20Hz and 20,000Hz. Hertz (Hz) is a measure of the number of wave cycles per second. A vibration at 20 cycles per second is very slow, and we would probably be *feeling* this very low "thunder" more than we really hear it. On the other hand, 20,000 is such a high pitch that most of us cannot even hear it—especially as we age or lose hearing from exposure to loud noise or bad marching bands. Although it is rare that a music recording spans 20Hz-20kHz or that a loudspeaker could accurately reproduce that wide of a frequency spectrum, we still will design, measure and expect our amplifier to be able to reproduce as accurately as possible this range of audio frequencies.

The charts of sine waves above (and visualized on an oscilloscope) are in the time domain, with frequency illustrated as the number of peaks and valleys over time on the horizontal axis. Another commonly used graph for audio measurements is in the frequency domain—a horizontal axis representing frequency from low to high, and the vertical showing a measurement of amplitude that a device may reproduce at each frequency.





The chart on the left here shows an example ideal flat frequency response that we might have with an amplifier: frequencies across the audible range of 20 – 20,000 Hz can be reproduced at an equal amplitude. The chart on the right shows an illustrative speaker frequency response—wow, it's very choppy, huh? There are some peaks and valleys where some frequencies are reproduced louder than others. This is typical of a speaker, where a very flat response is difficult to achieve and involves a wide range of physical implications in the action of the speaker drivers (woofer, midrange, tweeter), crossover points where drivers are transitioning responsibility, diffraction of sound from the shape of the speaker, and many others. In fact, the listening room will have a high impact on how we perceive the sound due to reflections. There is an extensive field of study of loudspeakers, room treatment, and other areas—more fun for the DIY hobbyist to explore! Just note for now that the frequency response of your speakers is incredibly important in achieving high-quality sound. It could require large and often expensive speakers to have a flat frequency response and one that extends down to the lowest ranges around 50 Hz and below.

A common measurement unit for frequency response is decibels (dB), a non-linear unit to measure the intensity of sound relative to a reference. If the reference level of 0 dB represents the threshold of human hearing, then a normal conversation might be 60dB in intensity, while a loud music concert could be 100-120dB. It is on a logarithmic scale because our hearing responds differently to low intensity sounds than it does to high intensity ones: 0dB is near silence, 10dB would be 10 times as powerful, 20dB would be 100 times as powerful, 30dB is 1000 times as powerful, and so on. A rule of thumb is that a 10dB increase is perceived as twice as loud.

In both charts, near the bottom and the top ends you see the frequency response start to fall off. On a response chart, the roll-off point that reaches -3dB point relative to a normal level is referred to as the cutoff point, where calculated power at that point is technically half of the 0 dB reference point. Measuring a response that fluctuates within 1-3 dB might be considered flat with minimal perception of change, but more than that could start to become noticeable in listening. For example, a speaker that could reproduce a flat response across a range, but rolls off with a cutoff at 100 Hz means it is down 3dB at 100Hz relative to the maximum level. As the rolloff continues it might be down 10dB by 80Hz (or half the perceived loudness of the higher frequencies) and you might feel it sounds thin or lacking in bass because these frequencies are not loud enough relative to others.

Ohm's Law: voltage, current and resistance

While it's likely you know this already, it's worth quickly highlighting the basics of a circuit: a closed loop involving **voltage (V)**, the difference in electric charge from one point to another, **current (I)**, the rate of change of electrical charge measured in Amperes (Amps), and **resistance (R)**, which opposes the current flow and is measured in Ohms. These three are the foundation to understand how a circuit is operating. Some type of power source creates a voltage that is higher in one place in the circuit relative to another. This voltage, sometimes referred to using a metaphor of "pressure", will force electrical charge to flow through the circuit as much as the resistance will allow, and this flow is measured as current. As current flows through the resistance, or the “load” of the circuit, the potential voltage drops until it is used up by the time the circuit is closed back to the power source.

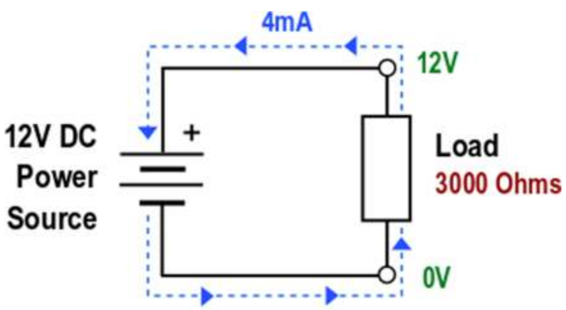
We can use one of the greatest magical formulas ever, **Ohm’s law**, which describes the relationship between these three (and we can solve for the third if we ever know the other two):

V = IR

I = V/R

R = V/I

In a **direct current (DC)** circuit, there is a source of positive charge and electricity flows in one direction. Perhaps the voltage source creates 12V DC, and the resistance in the circuit could be a simple resistor or could be some component that performs work when current is flowing, causing resistance or load on the circuit. In the example below, there is 12V of positive potential on one side of the battery, relative to the other side that closes the circuit. In between is a load that represents 3000 Ohms of resistance. Using Ohm’s law, we can calculate that this load will draw 0.004 Amps, or 4mA of current (I = V/R).



If there were no load, or no resistance, (essentially a short-circuit) then Ohm’s law would tell us there is 12V divided by 0 Ohms, or infinite current that would flow. This is obviously impossible in the real world, but we know that a short circuit will draw as much current as the power supply can provide, which could damage components, blow a fuse, etc.

Direction of current

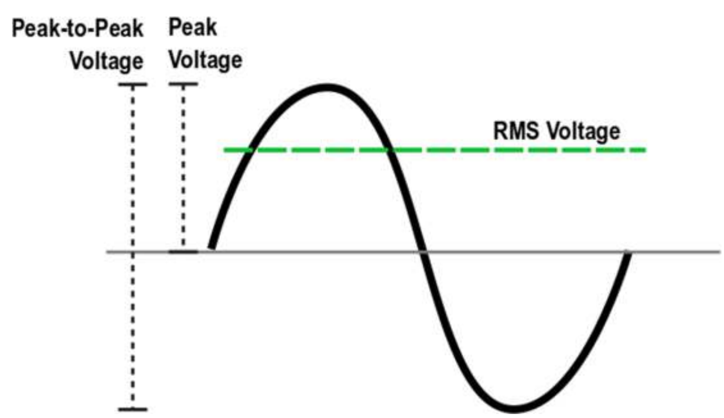
You will notice I drew arrows in the direction from negative to positive to represent the current. Don’t worry about direction. There is a history and convention of thinking about current flowing from positive to negative, and we often refer to a “voltage drop” that happens across the load that makes us think about the starting point being higher and moving to a lower potential. Electrons actually move from negative to positive. Don’t let it tangle you up. It’s two sides of the same coin. The key point is that there is a difference in charge between the two points in the circuit, and the amount of resistance between those points, as well as the amount of difference in charge (voltage) determines how much current (rate of change) we have.

Our houses use **alternating current (AC)** as the power source because of limitations that make it difficult to transmit DC over long distances. Alternating current is a voltage that changes rapidly back and forth from positive to negative at some frequency. In our homes, we have 120V AC at 60 cycles per second (Hz).

A circuit can have a load that functions on AC, such as a light bulb. But in many cases, an electronic device will need to convert the alternating current into direct current for the circuit to operate. We will discuss this process later when we go over power supplies and rectification.

Sound waves discussed in the first core concept can also be represented as AC voltages changing over time positive and negative at various frequencies or complex AC waveforms.

AC introduces a question if we wish to perform some measurements or calculations. What is the actual voltage of an AC power source if it is continually changing? We need a few more ways to describe this voltage. **Peak voltage** is the highest positive voltage in the cycle, and **peak-to-peak voltage** is the difference from the highest to lowest point in the cycle (usually twice the peak voltage). **RMS voltage** (root mean square) is a way to measure this AC voltage and express it as an equivalent DC voltage that would produce the same power dissipation. (Some digital multimeters can measure RMS voltage while others use techniques that estimate it assuming an AC sine wave.) RMS voltage can be calculated by multiplying the peak voltage by 0.7071.



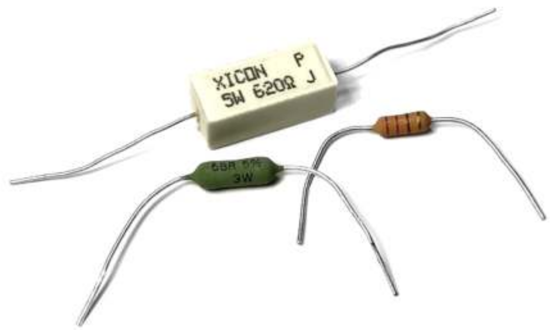
So in your home, if you measure the voltage from a wall outlet, it may be 120V RMS, but the actual peak-to-peak voltage is about 340V.

Power

Finally, while we are on the subject of Ohm's law and the voltage and current through a resistive load: **power (P)** represents the rate that energy is produced or used in a circuit. It is measured in Watts and is the product of current times voltage (P = IV). Or, knowing Ohm's law, you could calculate power knowing other combinations, such as resistance and voltage. For example, a circuit with 500 Ohms resistance and 24 volts of potential would dissipate 1.15 Watts of power. Hopefully this power is doing some useful work! Sometimes power may be transferred to heat energy.

Common Electrical Components

Resistors

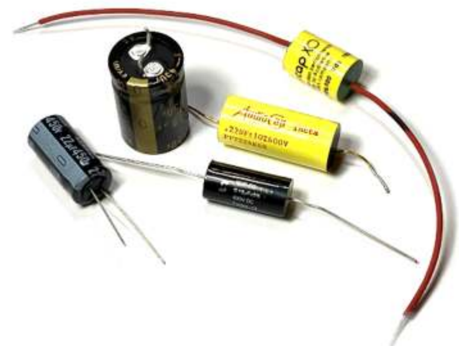


You are likely familiar with a basic resistor: a device that intentionally holds back current and is rated in Ohms. I won't go over these in much detail other than to mention briefly a few types of resistors and to cover wattage ratings.

Resistors are made in different ways and you'll see them categorized—metal film resistors, carbon film resistors, carbon composition resistors, wirewound resistors, etc. There are simply different ways to construct a resistor for varying objectives and you end up with different attributes, sizes, costs, etc. In my amplifiers I use metal film resistors and wirewound resistors, which tend to have the lowest noise. Noise is an unwanted side effect of a resistor that impacts the signal passing through it. It can be thermal noise, or current noise caused by the structure of the resistive material when current runs through it. While we want to minimize noise, this is not in my opinion the largest problem we need to deal with compared to many other aspects of circuit design and selection of high-quality components such as tubes and transformers. Resistors are relatively inexpensive components and have a pretty easy job to do if selected and rated properly.

Note that wirewound resistors are generally available in relatively lower resistances due to their method of construction. I use them typically for cathode bias resistors, which are often less than 1 kOhm. Wirewound resistors can be inductive, but in this application, it will not have a noticeable impact.

Resistors are manufactured with a power rating—1/2 watt, 1 watt, 2 watts, 5 watts, etc. As voltage is forcing current through a resistor, electrical power is converted to heat energy. The resistor is designed to handle a maximum amount of power before it is destroyed by too much heat—if you've ever made a mistake in a circuit, you will know you can easily burn up a resistor! Consider a circuit that has 100V causing 8mA of current to flow through a resistor that is 12.5kOhms (Ohms law validates these relationships). The power dissipated will be 0.8 watts (P = IV). So you would need at least a 1W resistor to handle this power. But a good rule of thumb is to use a resistor rated for double the power your circuit needs. I would select a 2W resistor in this case. There is no problem using an overrated resistor, other than cost and size. I often use 1W or 2W resistors even when power required is much lower because I buy them in bulk and they are physically larger than tiny ¼ or ½ watt resistors and my fingers can work with them better!

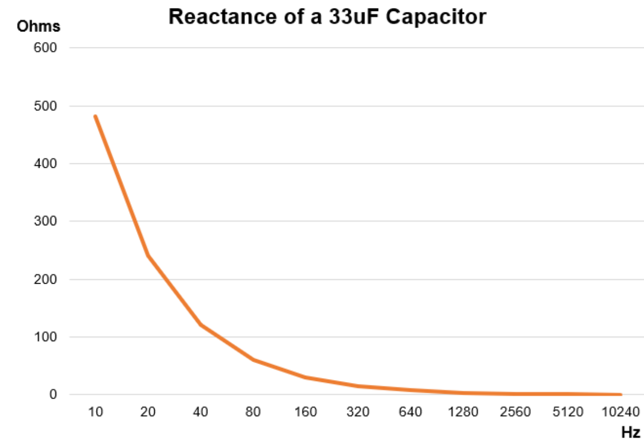


Capacitors

A capacitor stores energy in an electric field. It can be created in various ways, but commonly is done using two conductors (or plates) separated in some way, such as by a film or ceramic material or dielectric. There is no electrical connection between the two conductors, but because they are physically close, a voltage potential between them causes a positive charge to build up on one plate and a negative charge on the other. The physical characteristics of the capacitor determine how much energy can be stored in this way, and we measure capacitance using Farads, or more commonly microfarads (µF or uF), which are one millionth of a Farad.

Since there is no electrical connection, capacitors do not allow DC to pass through them. But a change in voltage will cause the plates to charge or discharge, allowing current to flow across the capacitor, so AC, as it changes rapidly from positive to negative, will pass across a capacitor. This is an important principle: the current in a capacitor is directly related to the rate of change in voltage—a very slow-changing or steady voltage will have low or no current, while a very fast change in voltage will have higher current. We can quantify the action of a capacitor to oppose lower frequency voltage changes using Ohms, the same unit of measure we use for resistance. But in this case we would refer to it as **capacitive reactance** (Xc). I promise I won't use many formulas, but you might find it helpful to see how we can calculate the reactance of a capacitor, since it will vary based on frequency and capacitance:

$$X_C = \frac{1}{2\pi f C}$$



For example, a capacitor that is 33uF in capacitance that has an AC voltage at 120Hz across its conductors would have about 40 Ohms of reactance at that frequency. What would you guess is the reactance at a lower frequency, like 60Hz? Yes, lower frequencies would have lower current passing, so it's a higher reactance of 80 Ohms. How about a very high audio frequency, like 8kHz? Plug that into the formula and you'll see the capacitor would present only about 0.6 Ohms of reactance. Cool, huh? And very useful! Visualized here is a plot of a 33uF capacitor's reactance at various frequencies.

One more example, let's see how this reactance changes based on higher and lower capacitance. Imagine this was a bigger capacitor of 150uF instead of 33. Now, because the capacitor can hold a greater charge, those same frequencies we just looked at have different reactance: 120Hz would have reactance of only 8.8 Ohms and 8kHz would have reactance of 0.13 Ohms. So a higher capacitance will lower the reactance at a given frequency.

Capacitors are rated for a certain voltage, and many are not manufactured with high precision in capacitance, often +/- 20%. Higher voltage rating and capacitance will require a physically larger (and usually more expensive) capacitor. Always choose a capacitor with a higher voltage rating than you expect it to see in the circuit. Exceeding the voltage rating will lead to the failure of the capacitor.

Capacitors, like resistors, come in a variety of types. For high voltage and capacitance values, we typically need to use electrolytic capacitors. These have a few drawbacks in terms of lifespan and some characteristics, but are still our best choice. Most electrolytics are polarized, so you must wire the negative side to the lower voltage potential or it can be destroyed or even explode. Electrolytic capacitors have a liquid inside of them and are sensitive to high temperatures and "ripple current" that can create internal heating of the capacitor, shortening the life if not rated sufficiently for the application.

In some cases when we have smaller capacitance needs, we can use some type of film capacitors. These are better for certain audio purposes than electrolytic capacitors, but would be too large physically for other uses when capacitance needs to be higher. You'll see in this circuit that we use a film capacitor for coupling between the stages of amplification—a sensitive part of the circuit where we don't need much capacitance. Audiophiles love fancy coupling capacitors and you can find some for outrageous prices, probably made by elves using ingredients that cost many gold coins and precious gems. I believe in good caps, but only so far, like most things.

Inductors

Inductors (some called "chokes") also store energy, but instead of an electric field as in a capacitor, it is stored in a magnetic field. These are usually made of some type of insulated wire that is wound into a coil, sometimes around an iron core. When current flows through the coil, a magnetic field is created. We can measure "inductance" with a unit called Henries (commonly using the symbol L) and it is based on number of turns of the wire, length and cross-sectional area and core material.

Under DC conditions through an inductor, current flows and a magnetic field is created. At this point, the inductor acts as though it were a short-circuit, with the only resistance being the natural resistance that the coiled length of wire would have.

However, when there is AC, the current is trying to change rapidly from one moment to the next. But when energy is built up in the magnetic field from increasing current, the inductor will tend to maintain that same level of energy, which is related to the amount of current. Think of it a bit like momentum and inertia: something put in motion will tend to continue in that same motion, or something not in motion will tend to stay not in motion. So when the current rapidly changes, the inductor resists the change. The net effect of this is that the inductor forms a voltage between its two connectors in opposite polarity to the change in current.

I know, this requires some heavy thinking, physics, force fields, ESP, and Jedi training to really get the theory of it, and I have not explained it with much depth. But the main takeaway is that inductors resist changes in current, and the voltage across the inductor is proportional to the rate of change of current. This is exactly the opposite of a capacitor, where current is related to the rate of change of voltage. Inductors have "reactance" similar to capacitors, that varies based on frequency. Higher frequencies will have greater inductive reactance than lower frequencies. The inductive reactance (X_L), measured in ohms, based on frequency (f) and inductance (L) is:

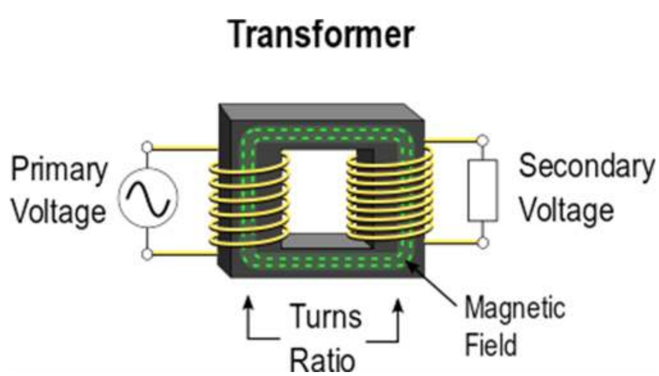
$$X_L = 2\pi f L$$

You will see an inductor (choke) and capacitors in this amplifier circuit performing important roles of blocking or allowing DC or AC, or filtering a power source to remove ripples in the voltage or current. I'm not touching on many other aspects of these components, including how phase of AC is altered by these components, but hopefully this gives some of the basics to understand our circuit.

Transformers

A transformer also uses principles of magnetic induction. Two coils of insulated wire can be wound on a core. When a voltage is put across one of the coils (the "primary" side of the transformer), it will magnetize the core and induce a voltage onto the other "secondary" coil. The two coils can have a different number of turns, and the ratio of these turns will result in a higher or lower voltage on the secondary side. This is very useful when we want to "transform" a voltage from one level to another. We use this in two places in an amplifier: to convert household mains voltage from 120V AC to some higher voltage needed in the amplifier circuit, and also after amplification to convert from a high voltage signal down to a low voltage usable for speaker outputs.

A transformer works with AC only. There is no electrical connection from primary to secondary, and DC would pass across the primary side as a short circuit (possibly damaging it). Remember how the inductor resists changes in current and will create a voltage to try and maintain its state of magnetic field? Under AC voltage conditions on the primary, a voltage will be created by the transformer on the secondary side as an inductive response, with current in opposite direction to the primary.



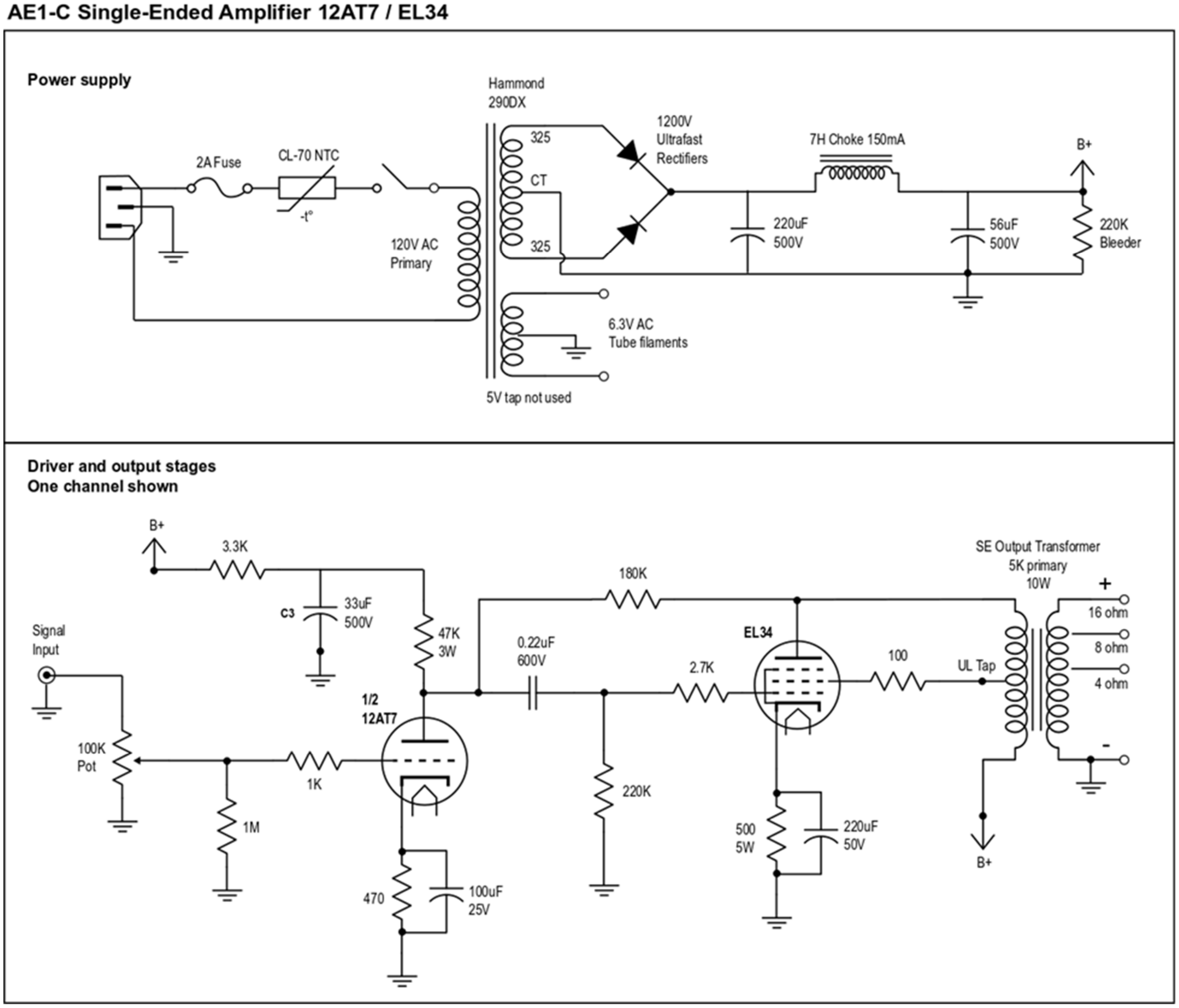
Keep in mind that this is a passive electrical activity (unlike an amplification process). We are putting the circuit load on the secondary side of the transformer where there is going to be a voltage, load resistance and resulting current draw. On the primary side, that load will appear differently due to the turns ratio so the current will also be different. If for example, a transformer has a 1:4 primary to secondary turns ratio, then voltage will transform from 120V on the primary to 480V on the secondary. A load on the secondary that results in a current draw of 100mA would have that current appear on the primary side using an inverse ratio as a draw of 400mA of current.

All that said, this is a simplified view and a transformer is not perfect, there are some losses in efficiency in several ways we won't discuss. Some power is dissipated as heat, and a power transformer can therefore become hot under a full load, and is typically designed and rated to allow for this.

Big picture of the circuit

We will go into detail on each part of the circuit, but for now, let's get up on the balcony and take a look at the big picture. Refer to the schematic, and you'll see one section is the power supply and the other is the amplification portion with two stages, driver and output. The driver and output stages are duplicated in the actual amplifier, one for left and one for right channel, but only one is shown for simplicity. There is, however, only one power supply for the circuit.

AE1-C Single-Ended Amplifier 12AT7 / EL34



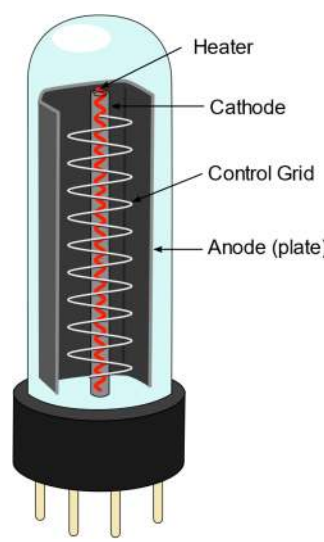
A later section will go over the power supply in detail, but for now, just know that the purpose of this portion of the circuit is to take AC voltage from your wall outlet ("mains" voltage) and convert it to high voltage DC, referred to as "B+". This is a historical term from when batteries were used as power supplies and this was the positive voltage. You may also see this referred to as High Tension or HT, also an older terminology. In our case, in comes the household 120V AC, and out goes the B+ of about 410V DC. You'll see later why we need this high of voltage.

The arrow on the right-hand side illustrates that the B+ is an output of the power supply circuit. That same arrow is shown in two places in the amplification part of the circuit (driver and output stages), indicating that the B+ voltage is used to supply power to two parts of the circuit. See those spots? Just a convenience in showing the power supply and amplification circuits separately instead of a single schematic.

In the driver and output stage, you can see the diagram flows from left to right, with the input signal entering on the left, the 12AT7 tube is a **triode** vacuum tube that performs a first level of amplification ("driver"), then the EL34 is a **pentode** vacuum tube that performs a larger ("power" or "output") amplification. We will also go over the details of these tube types and how they work. Finally, there is a transformer to convert back from high voltage to something usable for the output of the amplifier that will go to your 8 ohm speakers.

How does a vacuum tube work?

At the heart of this circuit is a vacuum tube doing its little magic. I will cover the basics of how vacuum tube amplification works so you can understand what's happening. I won't try to convey all of the physical science involved, but you are a lifelong learner I know, and can read more about it from others who can go into more depth and robust explanation.



Vacuum tubes used in amplifiers are also called "thermionic valves" referring to the way that temperature causes the release and flow of electrons. The basic type we will start with is a **triode tube**. Inside the glass enclosure of a triode tube are three main components: the **cathode**, the **anode** (also called the "plate"), and the **control grid**. There is also a **filament** to act as a heater.

The cathode is typically coated with a certain type of metal, and it is heated up to a high temperature. In some types of tubes, the cathode is directly heated by running current through it, but in most modern triodes (including the tubes in this kit) the cathode is heated using a filament physically close to it, but not connected electrically. The filament is what you see glowing inside of the tube, sort of like a filament inside a light bulb.

As the cathode reaches a high temperature, it begins to emit electrons. They build up in a cloud around the filament and, without any other action, eventually there are so many that the space around the cathode reaches a point where no more will be emitted. Why not? Because electrons have a negative charge and they hate being close to other negative charges, and all those other electrons bumping elbows are making the place pretty dang negative. What do electrons love? Positive stuff. They are attracted like crazy to it. So what would happen if we introduced something positive into the mix here? Yeah, those guys would go for it.

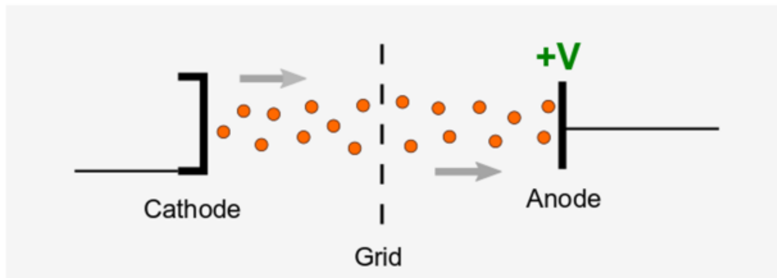
The anode is referred to as a plate because it's a metal plate surrounding the cathode, and we can put on the anode a juicy and delicious positive voltage with respect to the cathode. You will soon start to see why we need high voltage in a tube amplifier. If you just put a few volts on the anode, the electrons say, yeah man, cool, but I don't even get out of bed for that kind of voltage. To be sufficiently attractive, it has to be high.

The glass tube enclosure is sealed and there's a vacuum inside, remember? So those electrons are free to fly around without colliding into air molecules. So when there's a nearby high voltage potential on the anode, they are attracted and fly to it at ridiculous velocity, like around a million meters per second or something. Wow, right?

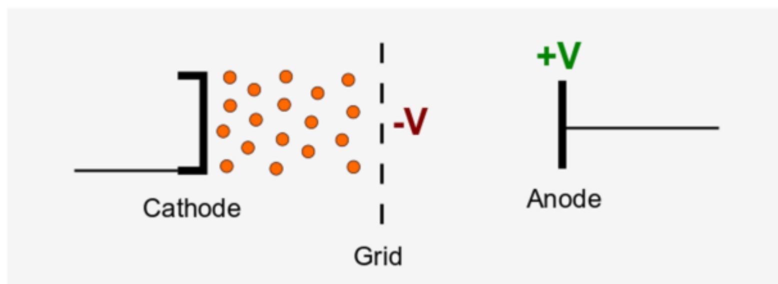
Now let's take a step back and think what's happening here. We heat up the cathode and it emits bazillions of electrons that flow at a million meters per second to the positive potential of the anode, continuously. Sounds a bit like…current? Yes. When the cathode is heated, electrons and current flows. (Don't get tangled up in directivity…the electrons go from cathode to anode, but we sometimes refer to current flow from positive to negative. It's just the way we measure current as a rate of change of electrical charge.) You'll note that it flows only one direction (a "diode" at this point). We heat the cathode and electrons can go to the anode. There is no way for electrons to go the other direction.

Alright, so an operating tube is allowing current flow (the "valve is open"). Now, there's one more component to make this a triode: the control grid. This is a wire mesh in between the cathode and anode that is spaced wide enough to allow the electrons to pass through. But what might happen if you applied a negative charge to it? You son of a turtle, say those electrons! We are not going through that negative fence you set up, we don't care what's on the other side. So now we have a way to control those electrons and if we raise or lower the voltage on the grid we can influence how strongly the electrons are repelled or allowed to pass. A very negative charge? No electrons pass and no current is flowing—we refer to this as "cutoff" of the tube. A less negative charge? Electrons and current flows (maximum flow sometimes referred to as "saturation" reflecting the temperature and physical constraint where the anode is pulling in all of the electrons that the cathode can produce).

1. When the grid is not negative with respect to the cathode, electrons flow to the positive voltage of the anode.



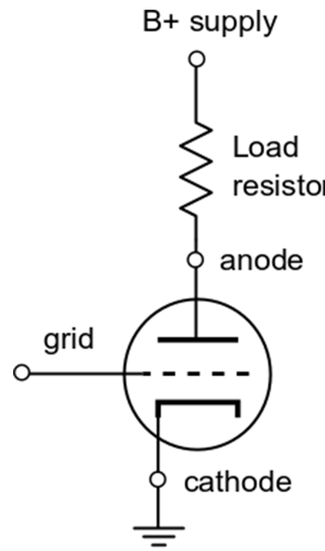
2. When the grid is negative with respect to the cathode, electrons are repelled and stay in the space around the cathode.



By altering the voltage of the grid, we can "open and close the valve," allowing current to flow more or less. Awesome! This is why a tube amplifier is sometimes referred to as a "valve amplifier." If we were to put an audio signal on that control grid, then the changing voltage over time of the audio signal will allow current to flow in alignment to the audio signal.

We are getting close! But how does this amplify the input signal? The answer is that the voltage change on the grid has a large influence over the current flow. How much current flow? To really understand, we need to get into a circuit a bit more and discuss load lines. You will love it. Hang with me.

First, we need one more quick addition to put the tube in context of a circuit. We already said that we would put a high voltage potential on the anode to attract the electrons and allow current to flow. We also will want a **load** on the anode, in this case a simple resistor, so that there is sufficient resistance in our circuit so we don't have an unreasonable amount of current flowing and also so that we can make use of the voltage change across that resistor. Ohm's law will tell us there is a known relationship between resistance, voltage, and current, right? And you love Ohm's law, right? Me, too.



Here's a very simplified circuit using a tube symbol. We won't worry about how we generated the B+ voltage or how we are setting the grid voltage, but assume the B+ is some high voltage potential, the cathode is at 0V, and the grid could be a few volts negative. We have enough for a working illustration of an operating circuit. (We usually do not show the heater filament in a tube schematic, so just know the heater is operating.)

For the sake of a quick calculation to get started, let's pretend that we have a 30k Ohm load resistor and 400V supply, and we pick a grid voltage that is allowing some amount of current to flow. How much current is there if we measure the voltage on the anode and it is 250V? Well, 150V must have dropped across the load resistor to get from 400 to the 250, and using Ohm's Law:

$I = V/R$

$I = 150 / 30{,}000$

$I = 0.005$ Amps or 5mA

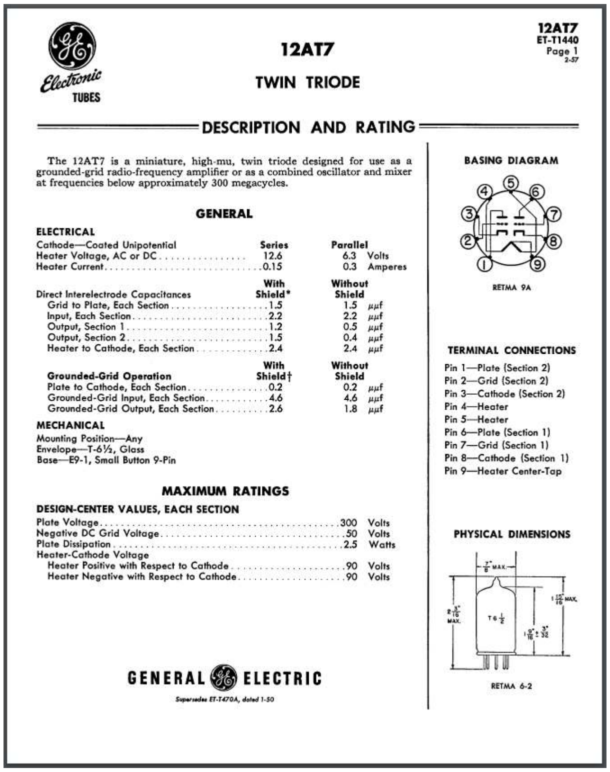
All we are doing here is using an easy technique to calculate current using a known resistance and measured voltages, using Ohm's law. But I want you to have the load resistor and Ohm's law in mind as we get a step further into the operation of the tube.

Tube characteristics, load lines, and operating point

The physical characteristics of each type of tube—materials, how far apart is the cathode, grid, anode, etc.—determine how the tube will operate and the effect of different voltages. Tube manufacturers provide datasheets that include a variety of information about these characteristics and limiting values. Search online and you'll easily find these as PDFs—often looking like bad photocopies of documents from the 1950s—and of course there's a long history of tubes from that era or earlier, so it's no surprise.

If you haven't studied these, they might seem confusing, but you are a brilliant learner and this is how you will be empowered to begin understanding or even designing your own circuits. Let's use our 12AT7 tube and take a look at an example datasheet:

12AT7 Datasheet (example pages)



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Electronic TUBES

12AT7

TWIN TRIODE

DESCRIPTION AND RATING

The 12AT7 is a miniature, high-mu, twin triode designed for use as a grounded-grid radio-frequency amplifier or as a combined oscillator and mixer at frequencies below approximately 300 megacycles.

GENERAL

ELECTRICAL

Cathode—Coated Unipotential	Series	Parallel	
Heater Voltage, AC or DC	12.6	6.3	Volts
Heater Current	0.15	0.3	Amperes

Direct Interelectrode Capacitances	With Shield*	Without Shield	
Grid to Plate, Each Section	1.5	1.5	μμf
Input, Each Section	2.2	2.2	μμf
Output, Section 1	1.2	0.5	μμf
Output, Section 2	1.5	0.4	μμf
Heater to Cathode, Each Section	2.4	2.4	μμf

Grounded-Grid Operation	With Shield†	Without Shield	
Plate to Cathode, Each Section	0.2	0.2	μμf
Grounded-Grid Input, Each Section	4.6	4.6	μμf
Grounded-Grid Output, Each Section	2.6	1.8	μμf

MECHANICAL

Mounting Position—Any
Envelope—T-6½, Glass
Base—E9-1, Small Button 9-Pin

MAXIMUM RATINGS

DESIGN-CENTER VALUES, EACH SECTION

Plate Voltage	300	Volts
Negative DC Grid Voltage	50	Volts
Plate Dissipation	2.5	Watts
Heater-Cathode Voltage		
Heater Positive with Respect to Cathode	90	Volts
Heater Negative with Respect to Cathode	90	Volts

BASING DIAGRAM

RETMA 9A

TERMINAL CONNECTIONS

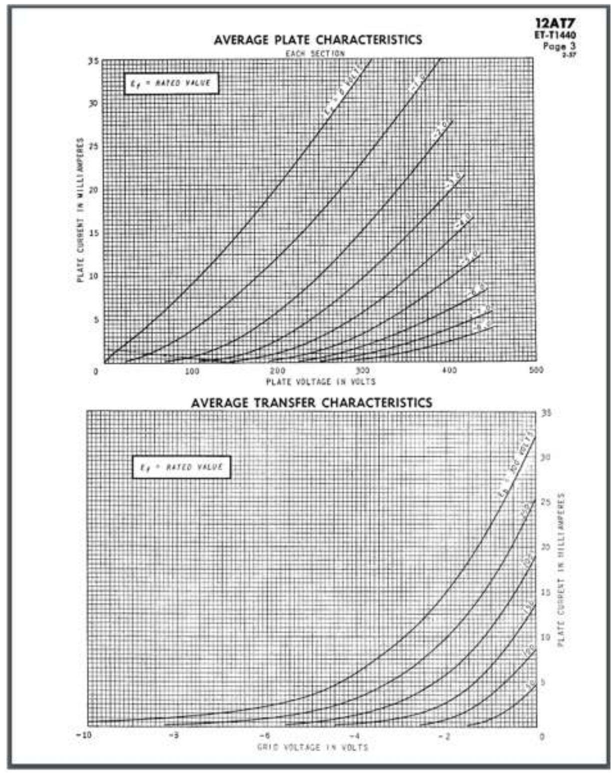
Pin 1—Plate (Section 2)
Pin 2—Grid (Section 2)
Pin 3—Cathode (Section 2)
Pin 4—Heater
Pin 5—Heater
Pin 6—Plate (Section 1)
Pin 7—Grid (Section 1)
Pin 8—Cathode (Section 1)
Pin 9—Heater Center-Tap

PHYSICAL DIMENSIONS

RETMA 6-2

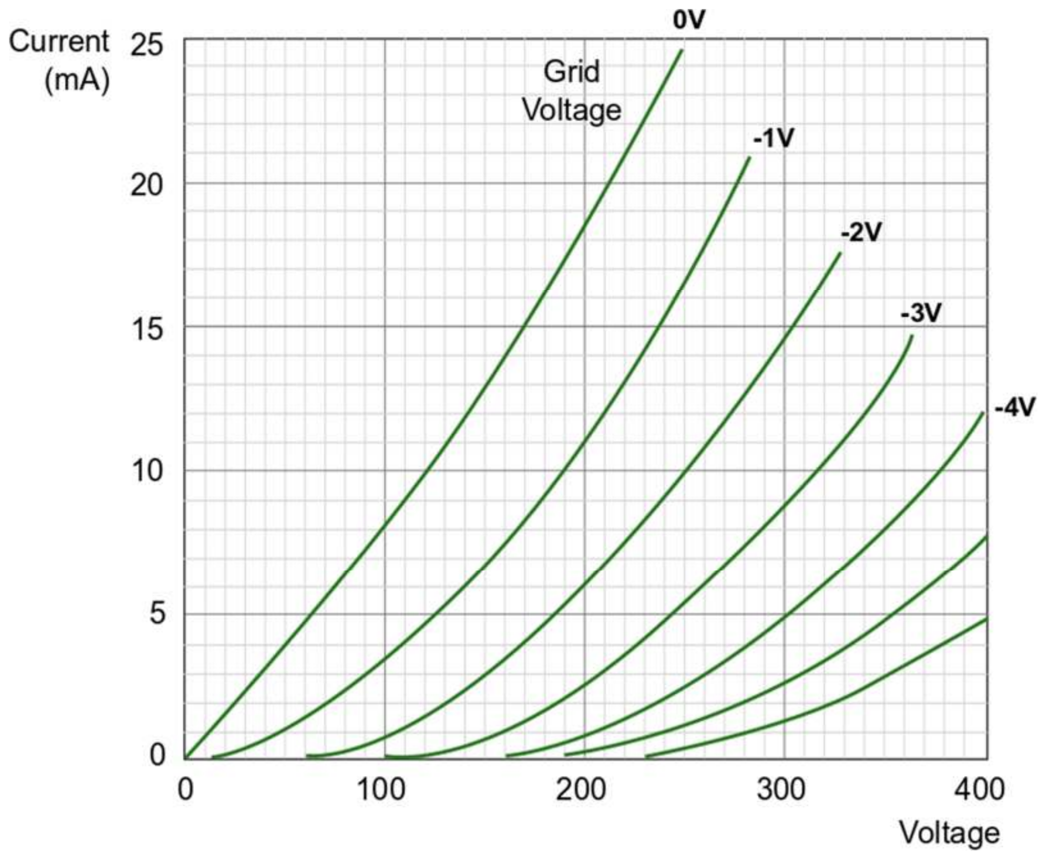
GENERAL ELECTRIC

Supersedes ET-T470A, dated 1-50

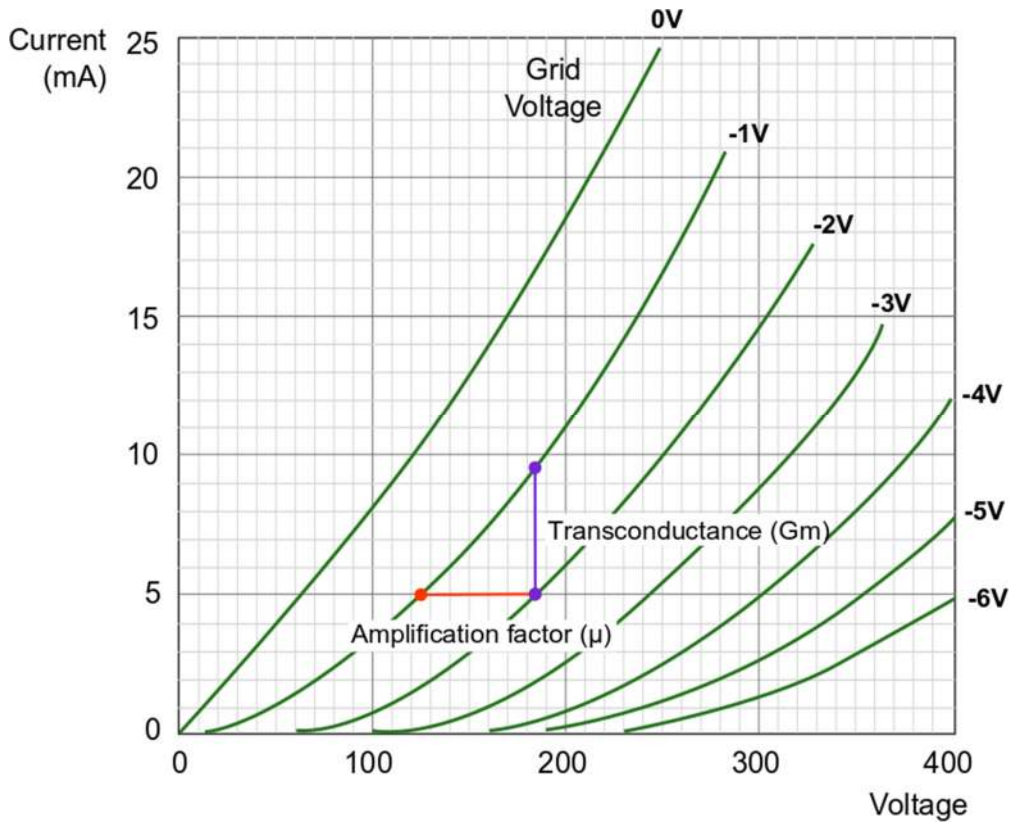


Go search for one of these online (e.g. "12AT7 datasheet") and pull one up for reference. We won't go into all of the details, but you'll find some useful information and I always keep these handy especially for the pin diagrams to tell you which pin number is the anode, grid, etc., or to know how much current the heaters will draw, or what maximum voltages can be used.

One of the charts you will find is the plate characteristics. On the x-axis is voltage and on the y-axis is current. There are a series of curves that represent different voltages that you could possibly have on the grid, and this will tell you what current would correspond to a particular anode voltage. Using the chart below, if you had the grid at -2V and you put 200V on the anode, then the tube (valve) will allow about 6mA of current. You will notice these are curves, not straight lines, because the tube does not operate as a perfectly linear device. We will talk about this later, regarding distortion.



Before we look at an actual circuit and load line, let's consider a few attributes of the valve that we can visualize on this chart. First, remembering that grid voltage controls the amount of current, let's see what this ratio is. If we pick a place on the chart and hold anode voltage constant and measure the distance between two grid curves, we can see that a 1V change in grid voltage results in around 4-5mA of current change. This is the purple line on the chart below, and is referred to as **transconductance** (Gm), often measured in a funny unit called mhos (reverse spelling of ohm, conductance being the opposite of resistance!) and tube datasheets usually use micromhos (one millionth of a mho). So look on the 12AT7 datasheet and you'll see transconductance of 4,000 – 5,500 (depending on operating conditions), which would match our chart estimate after converting units.



Now, consider another property called **amplification factor** (a ratio abbreviated with the Mu symbol: µ). Holding current constant, if we measure between two grid curves, we see that a 1V change in grid voltage will result in a change in anode voltage of 60V (red line above). Aha! Here is the leverage that we have been looking to understand. We could swing 60 volts of anode voltage for every one volt on the grid. Powerful, yah? So the µ of the 12AT7 is 60 and you'll see this on the datasheet. Some tubes have lower or higher amplification factors that could range from 20 to 100, for example. After we plot a load line and calculate the gain of the amplifier, you'll see that we won't expect to get this full factor of amplification in our application.[2]

Now let's take our basic circuit and consider what happens when we have a particular anode load. Let's say we had a load resistor that is 50k Ohms and we supplied 400V B+. If there was zero current flowing (tube totally in cutoff), what voltage is on the anode? Ohms law tells us that with no current, there would be no voltage drop across the load resistor, so the anode will have the full 400V. Let's plot a point at zero mA and 400V representing this extreme situation. And imagine the opposite end of the spectrum—what if the valve was wide open so that maximum current flows and the

[2] Techniques such as a regulated current source can be used to maximize amplification factor but will not be covered.

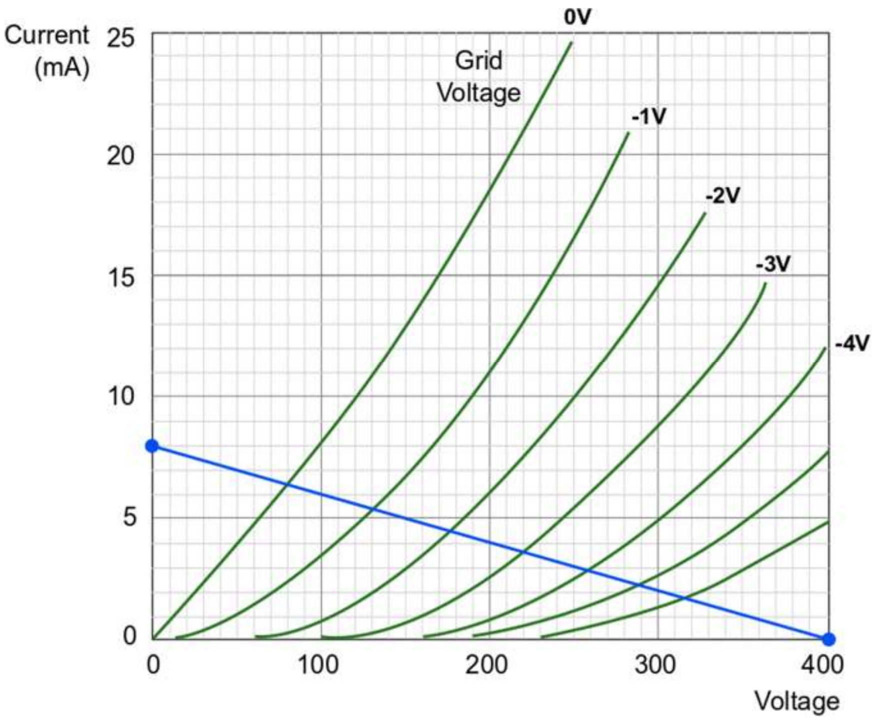
entire 400V were to drop across that resistor, and there was zero volts on the anode. Ohms law in this case to solve for current:

I = V/R

I = 400 / 50,000

I = 0.008A or 8mA

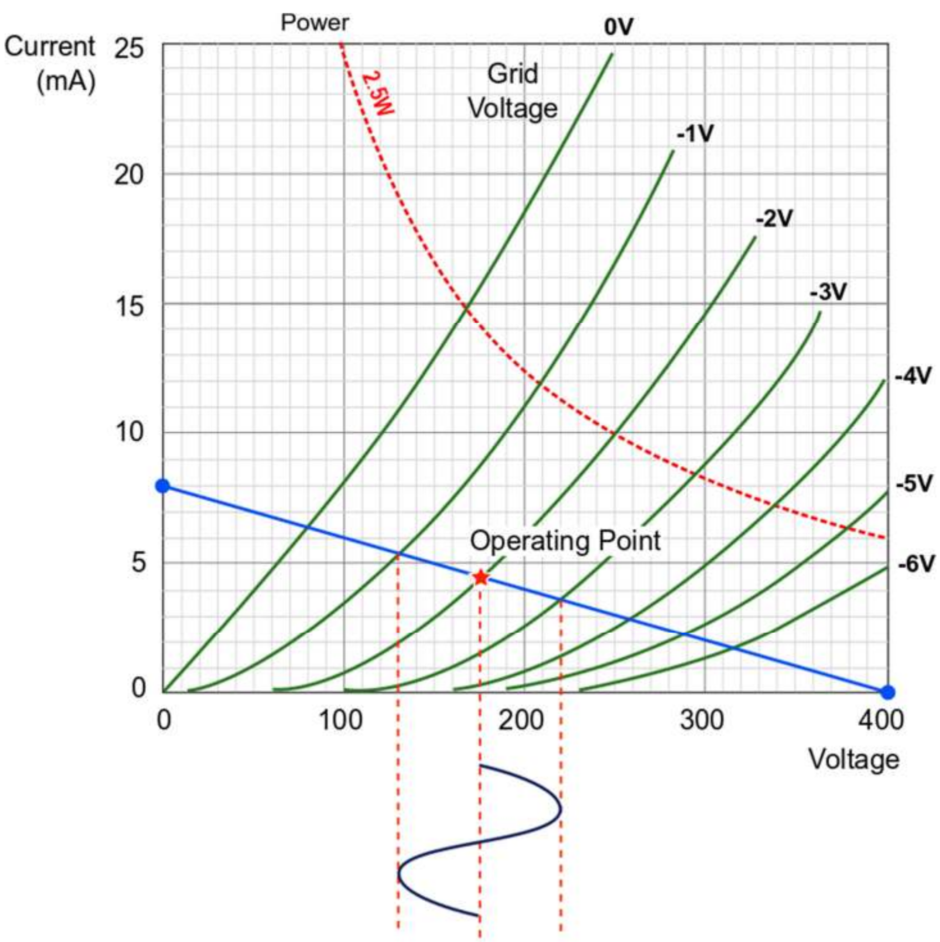
So let's plot another point at 8mA current and 0 volts on the anode. Ohms law is a linear relationship, so this is all we need to draw a load line between these two points.



So what we see here is the actual linear relationship between voltage and current for a 50kOhm load resistance and 400V B+ supply. Our tube must operate on this line somewhere. Where? That depends on what voltage we put on the grid. Look again at the grid curves and find the points that intersect with our load line. If we set the grid to -2V, then in this circuit we will have about 4.5mA of current and 175V on the anode. If we change the grid to -1V (less negative), then we will have 5.5mA of current and 130V. Notice that this is a change of 1V on the grid and a change of 45V on the anode—not the full 60 amplification factor because our load line isn't horizontal, it has a slope. If you were to alter the supply voltage or the load resistance, you can control the position and slope of this line, which impacts gain (and distortion).

Now it's time to visualize your audio signal on this load line. The input signal is an AC voltage that goes peak to peak from, let's just say, +1V to -1V (depending on your source level). If we simply put this signal onto the grid, it would cause the grid to fluctuate both positive and negative. We don't have any positive grid curves shown here. Why not? Because when the grid is positive it is attracting electrons just like the anode. This isn't what we intend and will leak current out of the tube through the grid, which would then further impact the voltage potential between grid and cathode, etc. It's a problem we will avoid by keeping our grid operating in a better space, more central on our load line.

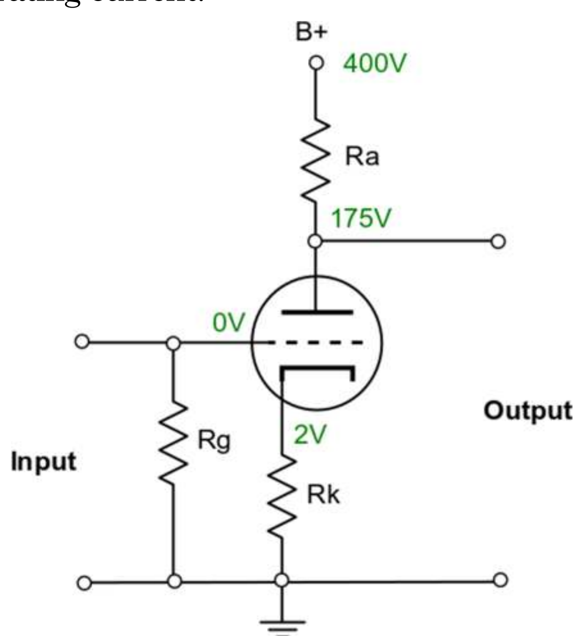
Let's pick a spot to represent the **operating point**, or the quiescent state when there is no audio signal impacting the grid, but there is enough room above and below this point for the audio signal to raise/lower the grid voltage. If we pick an operating point where the grid is -2V, this puts us roughly in the middle of the load line and there will be a steady-state current of 4.5mA, and 175V on the anode.



Now envision an AC audio signal on the grid that causes it to have a range between -1V and -3V and the anode voltage will fluctuate from around 130V to 220V. You can see a sine wave visualized on the horizontal axis. You should also recognize that we have current flowing continuously, it just varies in how much, based on the input signal and grid voltage. This is a **Class A** type of amplifier, conducting current across the entire input signal, not going into cutoff or saturation at any point. You can see that Class A consumes power continuously regardless of input signal amplitude and is therefore less efficient than other options, but it has excellent characteristics for high fidelity amplification and simplicity in our design. A **single-ended** tube amplifier uses one tube to produce an output, as opposed to other options such as a push-pull tube amplifier that would use two tubes amplifying portions of the signal.

One more consideration regarding load line and operating point. The tube will have maximum rated limits of operation. In the case of the 12AT7, the datasheet tells us that the anode cannot be higher than 300V in steady operation. So our operating point must be left of that point. And the tube is rated for maximum power dissipation of 2.5 watts. The red dotted line on the previous chart shows where current and voltage would exceed 2.5W of power dissipation on the anode, so our load line and operating point needs to be below that line.

Now let's figure out how to get our grid to be at our desired voltage for this operating point. One option is to use a negative DC power supply and adjust it so that it is 2V lower than the 0V potential of the cathode. Some amplifiers use this technique and it's referred to as **fixed bias**. It requires calibration to ensure the right relative voltage between grid and cathode to achieve a target operating current.



In our case we will choose another method. The grid needs to be negative with respect to the cathode in order to hold back the electrons, but we can achieve this in other ways rather than a negative DC voltage on the grid. We could keep the grid at 0V potential and elevate the cathode to a higher voltage. By inserting a resistor between cathode and 0V ground potential, we can put the cathode at a positive 2V potential so that the grid is now -2V relative to the cathode. This is a method called **cathode bias**. It's sometimes referred to as automatic bias or self-bias because if the steady-state current were to change for some reason (such as the tube aging and changing in properties), then by Ohm's law, the voltage drop across that resistor would change, so our cathode level would "automatically" adjust itself.

Ok, consider the new circuit shown. We inserted a cathode resistor Rk. What value should we use? If we want to elevate the cathode to +2V so that we have quiescent current flowing of 4.5mA, then Ohm's law will tell us that we need a value of:

R = V/I

R = 2 / 0.0045

R = 444 Ohms

Now we have technically increased our total load on the B+ voltage to the sum of the anode resistor and cathode resistor, so our original load line isn't quite right anymore, but this value is very small relative to the 50k Ohm so we won't worry about it, or you could re-calculate the load line with this larger value of 50,444 Ohms. (And of course 444 is an unusual number and we could round this cathode resistor value to one that is typically available.)

You will also notice a resistor Rg between grid and ground. This is called a **grid leak resistor**. We need something to reference the grid to the 0V DC potential, allowing the input AC signal to then be applied onto it to control the tube. We want this to be a high resistance value so that we don't attenuate the input signal (keeping the input impedance high relative to the source impedance), but there are some other considerations. There is a very small amount of current that flows in the grid ("leaking") and it could alter the bias of the grid. We will use a value of 1M Ohms here.

Congratulate yourself for understanding this far. We aren't done yet, but I hope you feel good about what you've learned so far. You might need to re-read a few times to get it, and consider additional resources I reference in the appendix if you want to learn at a deeper level. Pause here, get a Dr. Pepper, scratch dog behind ears, etc.

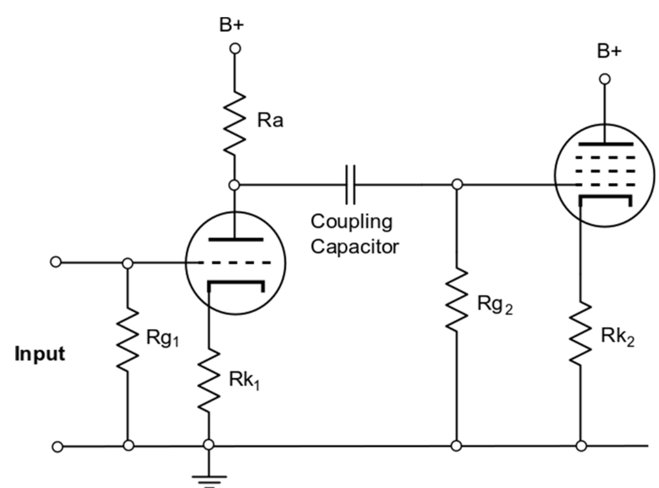
Coupling, AC load line, and cathode bypass capacitor

You have the basics. Now it's time to broaden our circuit a bit more and deal with a few more issues. The triode tube we have seen so far is used as a driver stage in our amplifier with still a relatively low level of current and output voltage. We need to put it through a power amplification stage to really get it to the level of current and amplification needed to drive our speakers and move some air on the journey of sound back to our ears!

We will take the amplified voltage from the anode, which you already know operates around 175V DC, fluctuating up and down with the audio signal. We can consider this an AC signal riding on top of the DC voltage. We will want to feed this signal into another tube—in our case an EL34 power tube—for further amplification, but we can't put 175V onto the grid. This high voltage will cause all sorts of problems on the grid which is intended to be negative, likely destroying it. We want only the AC portion.

The **coupling capacitor** is our solution. As you know, capacitors block DC and allow AC. The capacitance value can be small. We simply want to block the DC and allow all audio frequencies to pass. In our case, we will use 0.22uF as a commonly used and available value.

The coupling capacitor is directly in the signal path and so it is a very important component, and we want to use something high quality that will pass the signal without noise or distortion. Some type of film capacitor is best, and there are very high-end audiophile grade coupling capacitors produced, some at outrageous prices. This kit uses an Auricap XO brand that I believe is outstanding quality, but not at a crazy price. Note that the voltage rating of this capacitor needs to be high enough to handle the entire B+ because the tube takes time to warm up before any current flows, so the full voltage will appear on the anode, at least for a few seconds at startup.

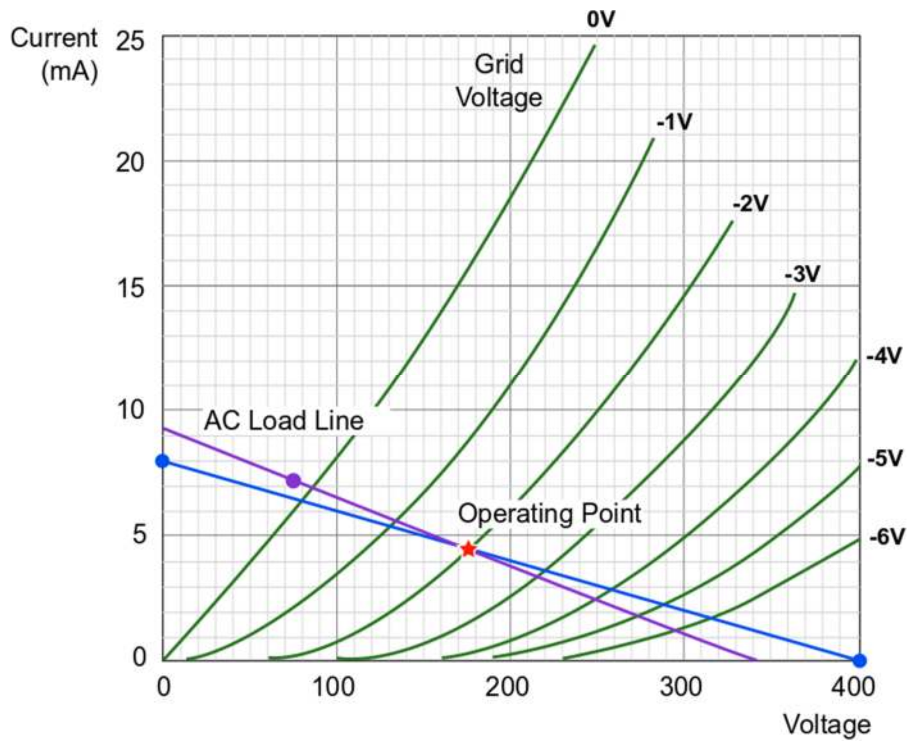


We will get into the output stage later, but we need to go back now and consider a few things with our driver stage. Our load line was fine for defining an operating point when there is DC voltage without audio (AC) on the grid, but since we are allowing AC voltage to pass on to the next stage through the coupling capacitor, we need another load line to understand the load under operating conditions: an **AC load line**.

The AC load will be the combination of two things: the anode load resistance we have already been dealing with, but also the impedance of the next stage, in this case a path to ground through the next stage's grid leak resistor. Do you see how Rg2 is in parallel with our driver tube (with regard to AC voltage, not DC)? Let's pretend that Rg2 is 220k Ohms. The formula to solve for parallel resistance is:

$$R = \frac{R_a \times R_{g2}}{R_a + R_{g2}}$$

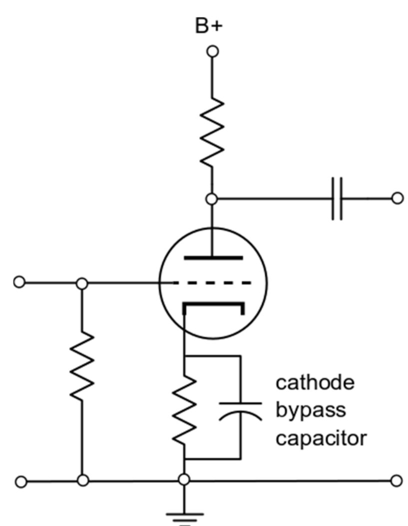
Solving this with 50,000 and 220,000 as our Ra and Rg2 values tells us that the AC resistance would be about 40.7k Ohms. Now, let's find our new AC load line. The operating point will stay the same, and we can choose to plot some other point to get our line. Let's pretend under AC voltage the anode drops by 100 volts. Ohms law will tell us that if our AC resistance is 40.7k Ohms, then the current difference for this voltage drop is 2.46mA. So we can plot a point that is 100V lower than our operating point, and 2.46mA higher in current. Now this is what our true working load line will be.



Our circuit is coming together! We will move on to the power stage soon, but first, one more problem to deal with. Remember how we wanted our cathode to be +2V relative to the grid. But think for a moment what is happening as the grid rises and falls with an audio signal—use a sine wave as an example and think about the voltage rising and falling over time. When the input signal is +1V, then the grid becomes less negative with respect to the cathode, and more current is allowed to flow. When more current flows, what will happen across our cathode resistor? Dang it. Voltage on the cathode will rise, right? Ohm's law again. On our AC load line, if the grid rises to -1V, then current is somewhere around 5.75mA. Remember how we solved to find our cathode resistor value and came to 444 ohms so our cathode would be at 2V. Well, 5.75mA across 444 ohms in Ohm's law is about 2.5V, instead of our intended 2V. The opposite is true when the signal goes the other direction: move down the AC load line, less current flows, which reduces the voltage across the cathode resistor. So the cathode voltage is fluctuating along with the input signal to some degree. Not what we want, and the net effect is that it counterbalances the amplification of the tube, reducing gain.

In some circuit designs, this can be used to an intended advantage (referred to as cathode degeneration), but in our design, we don't want this. Our solution is a **cathode bypass capacitor**. By putting a capacitor alongside the cathode resistor, we can hold the cathode at a desired DC voltage, but allow AC to pass through the capacitor. As the grid changes in voltage at audio frequencies, and current rises or falls accordingly, the AC currents will no longer impact the cathode voltage, it will remain at the intended 2V DC while the AC current can bypass it.

We will use an electrolytic capacitor because capacitance needs to be relatively high to allow current from low audio frequencies to pass. I am using 100uF in this particular circuit giving a cutoff somewhere around 3-4Hz. Lower cutoff might be better in some cases, so you could increase this to some higher value like 220uF, but our final output measures 1dB down below 20Hz, which is very good. The voltage rating needed is low given the expected voltage on the cathode. In this kit, I oversized the voltages a bit to use components that are a little bit larger and easier to work with physically (for example, using a 25V rating even though the cathode will only be around 2-3V).



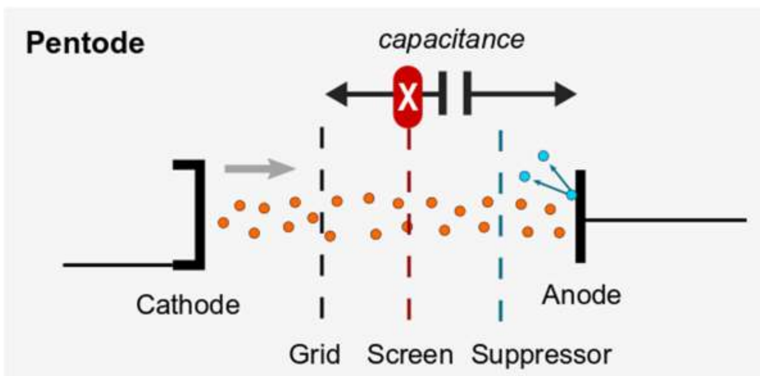
Output stage and pentode tubes

The tube used in our driver stage is a triode, which has great qualities, but also some limitations. You can read further material I reference in the appendix to understand at a greater level, but I will summarize briefly.

A triode has a small amount of undesirable internal capacitance that exists between the electrodes, notably between the anode and grid referred to as Miller capacitance. This caused problems in particular when attempting to use triodes for radio frequencies. To deal with this, new types of tubes were invented. First the **tetrode** introduced a **screen** in between the anode and control grid to shield the grid from the anode, reducing this capacitance. The screen could be held at a constant voltage while most electrons would still pass through to the anode.

However (there's always a however!) to make it work properly, the screen must be held at a relatively high DC voltage (usually lower than the anode), and this introduces a new complication in our expected current flow in the tube. At certain voltages, electrons will hit the anode with high velocity, dislodging extra electrons which bounce back and are absorbed by the high voltage screen instead of the anode. This is a form of emission from the anode, impacting its voltage at certain amplitudes of the signal, causing a bend in the grid curves, and distortion in the amplification process.

To deal with this side-effect, the **pentode** was invented[3], which adds yet another grid called the **suppressor** in between anode and screen, held at a low voltage (often tied to cathode) and this keeps those bounced electrons from being attracted to the screen, and they are then recollected by the anode. The electrons emitted by the cathode are moving at such a high velocity that the suppressor has minimal effect on them, only the deflected electrons.



The general principle of the power stage pentode tube is similar to the driver triode tube—put high voltage on the anode and screen, put the grid at a voltage that is negative relative to the cathode and modulate it with the voltage signal from the driver stage. But the output tube will be working with higher current and voltage swings.

The pentode screen grid has another effect on the tube, which is that gain is increased, and this is an attractive feature for a power amplification stage. Because the screen is held at a constant voltage, it continuously will attempt to pull a steady flow of electrons from the cathode toward the anode (as much as the control grid will permit), so the tube can conduct current more efficiently. This is different from a

[3] The beam-tetrode was also invented around the same time, solving similar issues in different ways.

triode where the voltage of the anode rising and falling with the signal is the only form of electron draw—for example, as the triode grid voltage moves more positive, current rises causing a drop in anode voltage across the load, but the lower anode voltage is less attractive to electrons than otherwise could be possible. This is a sort of headwind to realizing maximum triode gain that is solved with the pentode.

In our circuit, we are using one type of pentode tube, the EL34. Notice on the schematic the bottom dotted line is the grid, the next one is the screen, and the top one is the suppressor. Note that a pentode tube could be made to operate in triode mode by simply connecting the screen to the anode so they are always at the same voltage. Some amplifier designs do this and we will discuss soon some choices of how we will actually use the screen in ultralinear mode versus pentode or triode mode.

On the schematic, you can see again we have another grid-leak resistor. And a cathode resistor with bypass capacitor. And an anode load—oh, wait…where's the load resistor? The B+ in the output stage is going into the output transformer primary, and out the other side of the primary, to the anode. Aha! We don't have a resistive load in this case, we have the speaker as the load, and the fluctuating voltage across the transformer is going to drive—or do the *work*—of moving the speaker coil. But speakers are not designed for high voltage (and it wouldn't be safe to have this exposed outside of the amplifier anyway), so the output transformer will convert our amplified plate voltage to a different voltage and current level suitable to drive the speakers.

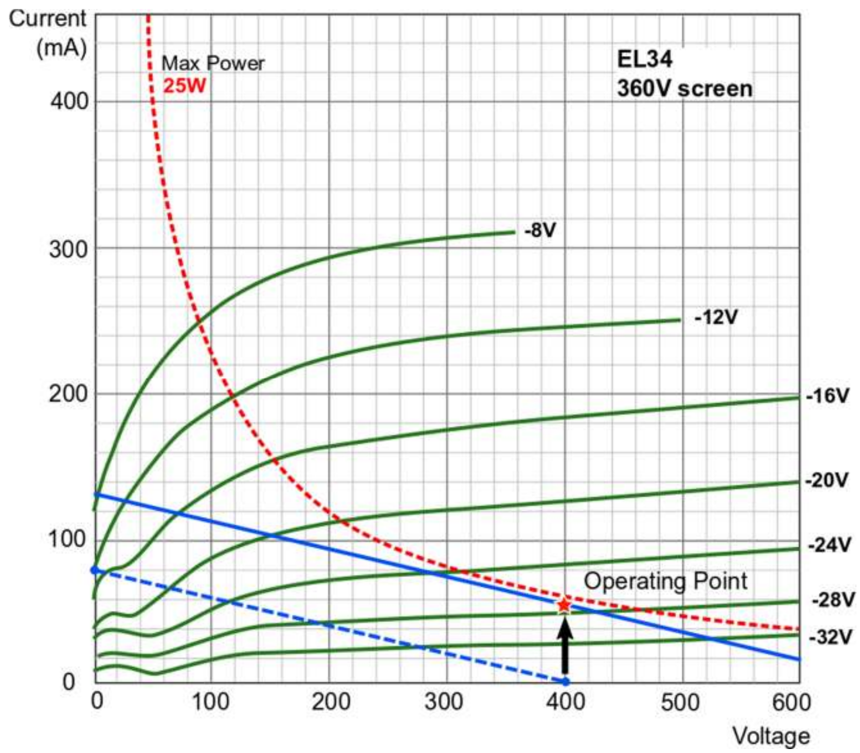
Ok, you are saying, but wasn't the whole point to amplify the signal? Are we reversing our process? No. Remember that the transformer will transfer the same amount of power from the primary side to the secondary side, but the number of windings in the transformer will determine how current and voltage are changed. In our case, we are lowering *voltage* down to levels below 10V, but for power to be the same, *current* must increase. So we will have a large AC current driving our speakers. This is a transformation to the final step of our audio signal and we hope our trusty output transformer does this as a faithful and accurate reproduction. The quality and size of the output transformer is very important in maintaining a flat frequency response across a wide bandwidth at our desired output power. The kit includes Transcendar brand transformers, made in the USA, that I believe are outstanding quality and one of the most expensive components in the kit because they are made to order. There are smaller and larger sizes of transformer ("iron" as you might say to your DIY tube amp buddies), and larger ones will be heavier and more costly, but also will ensure a wide bandwidth and flat frequency response at higher rated power output. The takeaway is that not all are created equal, so this is one place in your amp where you want to choose carefully a trusted and high quality manufacturer.

So if the speaker is the load on the power tube, how big of a load is it and can we calculate the load line again? You may be using an 8 ohm speaker impedance, but the windings ratio of the transformer will make this impedance look much larger to the tube which is what we need for the tube to operate properly. We select this ratio when choosing the output transformer. Our design will use a transformer that will be 5,000 ohms on the primary side of the transformer for an 8 ohm secondary impedance. You could choose a transformer with different values, depending on the load you want on the tube and the impedance of your speakers. Some transformers are made for a single speaker impedance, but the ones included in this kit have multiple taps so they can be used with 4, 8, or 16 ohm speakers depending on which one you use. And 5,000 ohms gives us a load that will work effectively for our supply voltage and characteristics of the EL34 tube.

Speaker impedance

It is important to remember that the speaker is not a uniform resistance of 8 ohms. All speakers have impedance that varies with frequency. They are rated typically at 4 ohms, 8 ohms, 16 ohms, but this is just a nominal value generally close to the overall impedance. A typical 8 ohm speaker could actually have a wide range of impedance from 3 or 4 ohms at some frequencies or 10 or 20 ohms or higher at other points. The job of the speaker is to reproduce frequencies as uniformly as possible across the audible frequency spectrum, and there are physical properties to the cone and suspension and a wide range of other things that will cause the impedance to be higher or lower across frequencies.

So if we know the B+ in our circuit is 400V and we have a 5,000 ohm load, we can start to work on a load line and operating point. Like the triode tube in our driver stage, we can look at the tube characteristics provided by the manufacturer. The process will be a bit different because this is a pentode tube and because of our output transformer and speaker load. One challenge is that the load lines will vary depending on the screen voltage. Sometimes the datasheet will have multiple charts for different screen voltages. Below is one for 360V, which is relatively close to our expected voltage that we could put on the screen. It’s ok if this isn’t perfect, we are just getting somewhat close to the theoretical operating point and it becomes important to test and modify the circuit in actual operation to optimize it anyway.



In the chart shown, the blue dotted line is the initial load line for 400V and 5,000 ohms (which would be 80mA of current if all 400V were dropped). But remember that we do not have a resistive load. (Actually, the transformer has a small amount of DC resistance in the primary winding—but this is relatively small so we will ignore it for now.) So at the quiescent point with no AC signal, nearly the entire B+ voltage will be on the anode, so our operating point voltage must be around 400V. But if we stay on our initial load line at this point, it would not be useful because it's at cutoff and could then only amplify the positive side of the signal. We need to bias the tube and move this load line up.

What we will do is choose an amount of current that we want at the 400V operating point. To maximize our power from this tube, let's pick a level just below the maximum rating, shown with the red dotted line. Approximately 60mA of current would keep us under the 25W maximum. So we shift our load line up, keeping the same slope until we reach an operating point that is 400V and 60mA. Finding the nearest grid line, this is pretty close to -28V. See that? (For simplicity, let's just pick -28V, though we could try to estimate -27V, etc.) Now, if we need -28V on the grid relative to cathode, then we can again use the cathode bias technique and hold the grid at 0V while we elevate the cathode to +28V. Using Ohm's law, if we are estimating 60mA of current dropping across 28V, this gives us a resistance of 466 ohms, or let's pick 470 which is a common resistor value. This will dissipate about 1.7W of power, so we would choose a resistor rated at least double for a margin of safety, such as a 5W resistor. We will again bypass this resistor with a capacitor, this time a 220uF electrolytic capacitor rated for 50V.

Are you still with me? I know it's a lot, but you are getting it, right? Summarizing for a moment… we put 400V on the anode and because there is little resistive load under DC conditions, this is our operating point voltage. We elevate the cathode to 28V and our tube will be dissipating 60mA of current in its quiescent state, shifting our load line up. Now under AC conditions the signal will vary the voltage of the grid by say 10 volts or so depending on input level and amplification in the driver stage, and this will swing the anode voltage very widely, up to a few hundred volts. And importantly, it will put this alternating current across the transformer, transferred back down to a low voltage and higher current to drive the speakers. Notice here that the anode voltage can actually rise higher than the B+ supply because the transformer stores energy in its magnetic field and it will resist the change in current, causing it to create a temporary higher voltage.

A few more quick notes. We haven't illustrated the AC load line in the chart, and will not try to do this because the speaker impedance varies across frequencies. But you could visualize an AC load line pivoting around this operating point, sometimes a higher load and sometimes lower, altering the slope of the line, but always around the operating point. At this time, we know enough about the operating point of the circuit to have our initial design and can modify if needed.

We also need to get back to that screen. You thought I forgot, didn't you? Take a break, get a snack. Almost there!

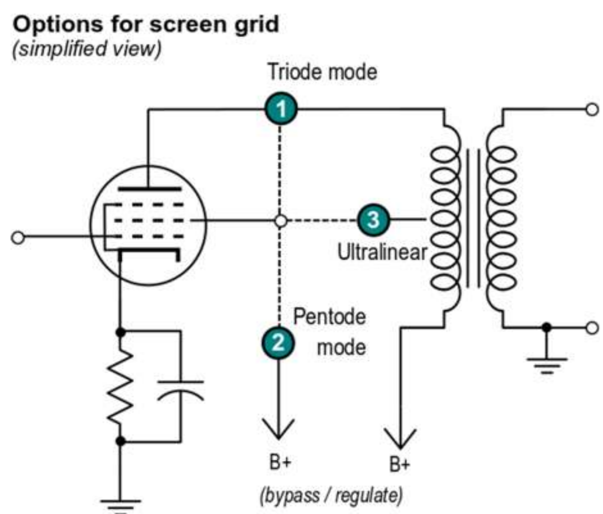
Screen voltage and Ultralinear mode

There are several options for how a pentode tube can be operated. This kit is designed for **ultralinear mode**, and so I will not go over a circuit for a standard pentode design in much detail. But I will cover a few basics so you understand the options and how ultralinear mode fits into those options.

First, and simply, you can take any pentode tube and operate it like a triode ("triode mode" or "triode strapped") by simply connecting the screen to the anode, and the voltage of each will always be identical. Both the anode and screen will swing together in voltage across the output load as a signal is applied and current passes through both of them. Output power will be lower, and the tube characteristics will generally have more lower order harmonic distortion—some consider this a desirable "sound" for a tube amplifier, though obviously perception of sound is highly subjective. The grid-curve chart shown earlier for the EL34 is not in triode mode and would look different if the tube were triode-strapped.

Second, to operate in pentode mode, you would put a DC voltage on the screen at around the B+ level or somewhat lower, and then you would also bypass the AC by using a capacitor to ground (not shown) so that your screen stays at a constant voltage. Only the anode will swing in voltage as the signal is applied. Pentode mode will have more power output possible, and generally produces more higher order harmonic distortion—some would consider a less pleasing sound, again a subjective generalization. (I know I have just mentioned a few types of distortion and have not discussed this topic much yet; we will come back to it soon in more detail.)

Ok, these are two fine options. But some clever folks in the 1950s made a discovery of a third option that has very interesting results. You could think about triode mode and pentode mode as two ends of an extreme with respect to the screen voltage. On the triode end, the screen voltage is entirely determined by the anode (plate) voltage which means it changes with the audio signal, and on the pentode end the anode voltage is completely independent and the screen voltage is held at a constant level.



Each of these modes has their own form of non-linear distortion, but they tend to curve in opposite directions. If we were to take a position part-way in between these two extremes and put that on the screen, there's a sort of magic that happens at the right spot where we can get a more linear operation (less distortion) and still get most of the benefits of pentode mode for power. By putting a special tap on the output transformer, we can vary the screen voltage in proportion to the anode but not as much as in triode mode. It was found that a tap around 40-45% of the primary is the ideal spot. This was called "Ultralinear." It could be considered a form of negative feedback.

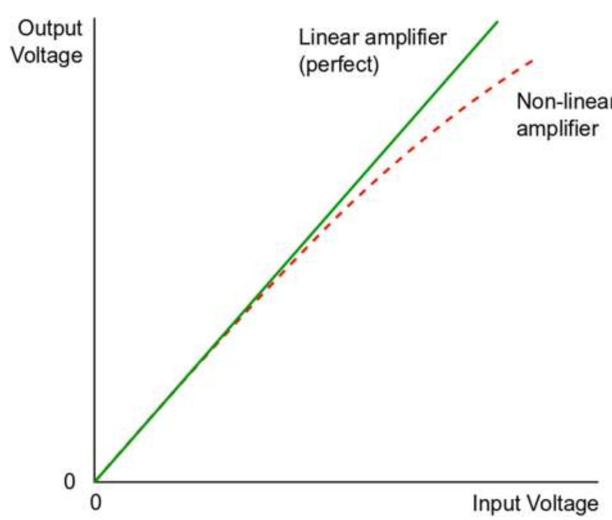
There is deeper theory of ultralinear operation you can study elsewhere. It's used in our case to have optimized performance: good power output and low distortion. Critics of ultralinear might believe triode mode sounds better or pentode performs better, but in my opinion this is a good option given design objectives of low distortion, simple circuit design and sufficient power output from the selected components.

You can re-wire this kit to operate in triode mode by connecting the screen to the plate and tying off the UL tap of the transformer. You would still want a resistor on the screen pin (not illustrated here) for stability reasons to prevent oscillation, similar to a grid stopper resistor we will also put on the control grids. In our circuit we use 100 ohms to control stability, but you might consider raising this a bit higher if you run in triode mode, such as 1k or so. The screen is a sensitive part of the tube, and the datasheet will tell you the maximum voltage and power dissipation of the screen. Most EL34 tubes are rated for around 425V on the screen and about 8W of power—notice that there is some current passing through the screen as some electrons will be hitting it, even while most are passing through and on to the anode.

Understanding distortion

It's time to try and cover the topic of distortion. It certainly sounds like a bad thing for a high fidelity amplifier, but what exactly is it? Let's take a closer look, and we may dispel a myth or two in the process. First, I should say that there are multiple types of distortion, and I will mainly be discussing one type here, **harmonic distortion**, which is commonly analyzed in an amplifier—and even this we will only just begin to explore.

In a perfect amplifier, we would have an input voltage that varies over time (the audio signal) and an amplified output voltage that varies over time exactly proportional to the input voltage but at a larger amplitude. We want this to be a **linear** relationship: $V_{out} = V_{in} * gain$, no matter what level of V_{in}. As the input voltage rises, the larger output voltage rises proportionally.



But in the real world things are not perfect. Perhaps over the range of possible voltages, the tube is doing its best (c'mon give the guy a break!) but as the input voltage on the grid moves up and down, the output voltage on the anode is changing in a similar, but not exactly identical way across all voltage levels. Perhaps we would expect 1V input to result in 10V output, but the amplifier actually puts out 9.5V.

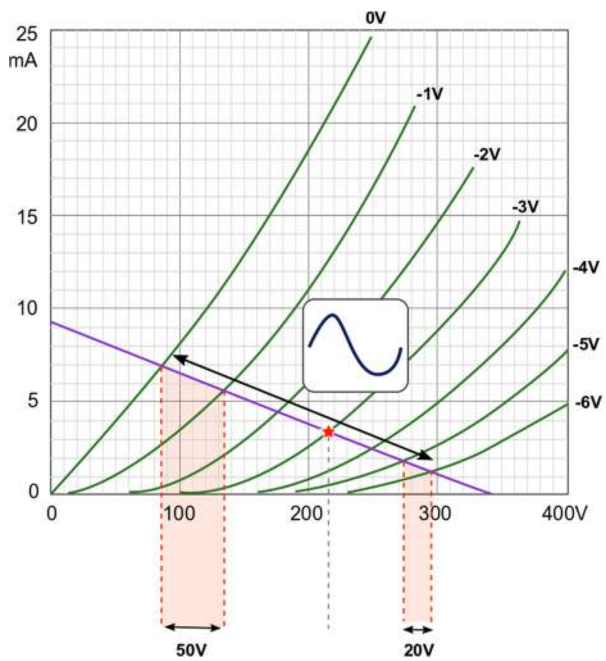
This non-linearity of the range of output voltages relative to the range of input voltages is distortion. This is an attribute of all tube amplifiers, and some might argue part of their “tube sound.” In that respect, zero distortion might not actually be the goal, but certainly we want the output to be as close a representation of the original as possible, so we will aim to have relatively low distortion.

Ok, so how can we visualize and understand distortion even more? First, I want to emphasize one important point. The amplifier has no idea about the concept of an audio signal or sine wave, which incorporates *time*. The tube is not first listening to your Bob Dylan song and then playing it back to you louder, nor is it looking at a sine wave for a millisecond or two and then recreating a new sine wave afterward, hopefully similar. The amplifier sees an input voltage at a point in time and puts out an output voltage at that exact point in time, or close enough to consider instantaneous. This will be important as we get into visualizing distortion and discussing feedback. We use sine waves to communicate concepts of frequency and distortion, but the behavior of the amplifier occurs at a single point in time. That said, there are elements of time in the ability of the amplifier to react quickly to fast changes in voltage and demands on current in order to perform its job properly at the present point in time, but the point I’m making is that we need to consider distortion of a sine wave as an effect that we observe over time, but that is happening at any given instant.

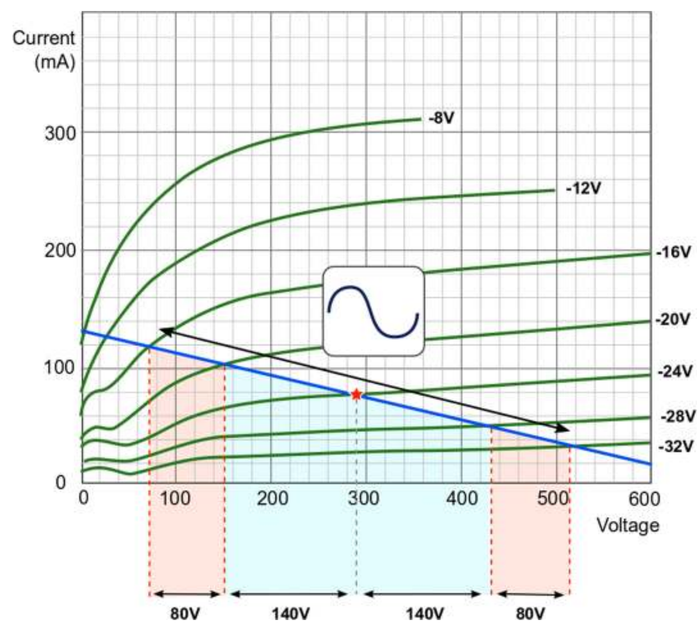
Now let’s reintroduce the concept of time and consider a sine wave as a voltage changing over time, and the output voltage isn’t perfectly identical in shape to the input sine wave. Remember how we drew a straight load line, expecting that variation of the grid voltage would cause the anode voltage to swing up and down on that line. But if the characteristics of the tube means the grid lines are not evenly spaced apart, then we can’t expect the output to be a perfect replica. Two examples are illustrated below, where grid curves are either closer together at one end, or at both ends, causing non-linearity.

Examples of harmonic distortion

If grid curves are wider on one side than another, gain is asymmetrical, creating even-order harmonic distortion:



If grid curves are wider in the center than at the extremes, this causes symmetrical odd-order harmonic distortion



You can see in these examples that an equal change in grid voltage would not cause a proportionally equal change in anode voltage at all areas of the load line. When the gain is asymmetrical around the operating point, the output waveform will be misshapen, or **distorted**, on one side but not the other. This will cause a type of harmonic distortion that is even-order. If the non-linear effect is symmetrical on both sides of the waveform, then this causes odd-order harmonic distortion.

You might also consider what happens if the operating point were too far to the left or right on the load line, or if the input signal were too large relative to the span of grid curves—if the input voltage pushes into saturation (near or above 0 volts on the grid) or down to cutoff (deeply negative grid curves, with low or no current), then obviously the output signal will be extremely distorted and a sine wave would appear as flattened on top or bottom. This is what we would refer to as **clipping**. Guitar amplifiers operate closer to these conditions to achieve a desirable overdrive or distortion sound, but obviously in a hifi amplifier, this is undesirable.

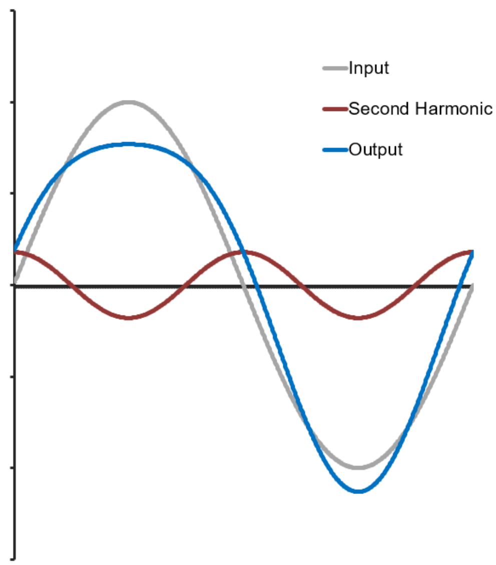
Now, we're finally ready to look at harmonic distortion another way to visualize these even and odd-order harmonics! I love this part, because the natural world, physics and math are sometimes like magic.

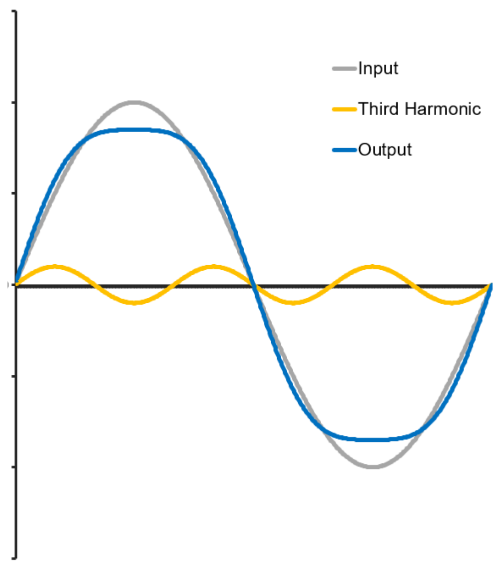
The sine wave that we input is at a frequency, let's say 1000 Hz. We can call this the **fundamental frequency (FF)**. Multiples of this frequency are the **harmonics**: the second harmonic is 2x the fundamental frequency, or 2000 Hz; the third harmonic is 3x the fundamental frequency, or 3000 Hz; and so on…fourth, fifth, etc.

An output sine wave that has been distorted by a non-linear amplifier will have a waveform that doesn't look exactly like the original sine wave. And this distorted waveform is equal to the fundamental frequency plus some combination of harmonics at lower amplitudes. See the charts below that are illustrative examples if we took a pure sine wave input and add a second or third harmonic at lower amplitude. The output is a combination of those frequencies added together.

Distorted waveforms

In both examples here, the blue distorted waveform is equivalent to the combination of the input sine wave and a second or third-order harmonic (at 2x or 3x the frequency).





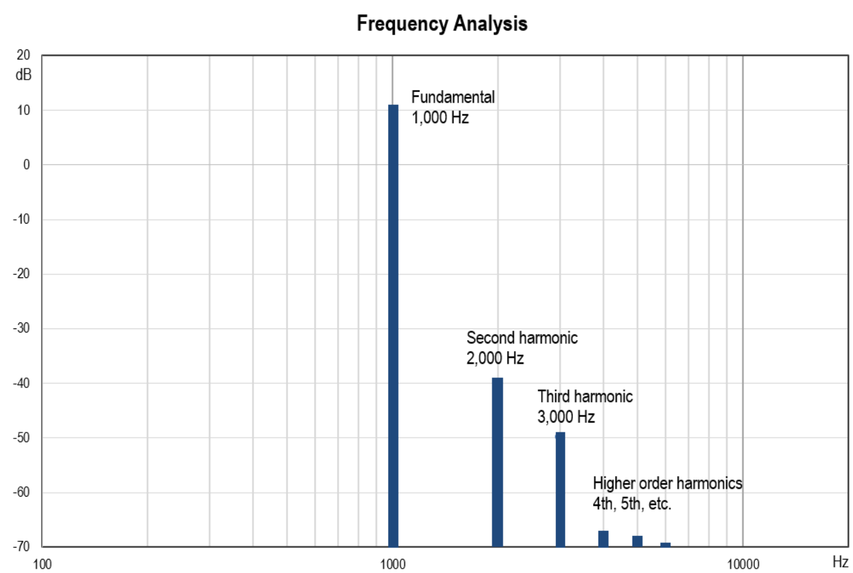
Are you getting it? The distorted waveform is **the same** as multiple sine waves at different frequencies and amplitudes added together.[4] Going back to our amplifier, it's important to re-emphasize: the output waveform is distorted due to various causes, and this is *equivalent* to a fundamental frequency plus harmonics. We could be tempted to have a mental image that the harmonic frequencies are created in some other way and then added to the original signal, with harmonics as the cause of a distorted output. I suggest this is not the best way to think about it. Remember how I pointed out that amplification is happening instantaneously. The waveform is

[4] Harmonics may also be at a different phase than the fundamental frequency, but this is not introduced here. For illustrative reasons, the second order harmonic shown here is offset by 90 degrees in phase.

distorted because gain is not uniform across all input levels, and when that happens, we can watch a waveform over time that can be described as the original fundamental frequency plus harmonics. The net effect is, however, exactly the same as if we did truly have multiple sine waves generated at different frequencies, amplitudes and phases and combined together.

What this means is we have a way to measure the harmonic distortion of the amplifier. While you could look at the waveform on an oscilloscope and subjectively say, "well, it looks pretty close to a sine wave," and this is fine for basic observation and detection of significant distortion, we can do better.

Since the distorted waveform is identical to multiple sine waves at different frequencies, we can measure and visualize the amplitudes of those harmonic frequencies. Here's where we need a new graph: instead of showing amplitude versus time of a waveform, we can show amplitude versus frequency. A frequency analyzer can do this for us. Below is an illustrative chart demonstrating measurements of harmonic distortion on the frequency spectrum.



You'll see this uses decibels for the vertical amplitude, with a 1000 Hz fundamental frequency at a certain level, and the second harmonic is much lower about 50 dB below the FF. The third harmonic is lower still, and very tiny amounts of higher order harmonics. This is typical of a single-ended tube amplifier: most distortion is second and third harmonic.

We could then calculate a summary measure to add up all these harmonics and this is what you see reported as Total Harmonic Distortion (THD) usually as a percentage of the fundamental frequency. High quality modern solid state amplifiers will have extremely low values, like 0.01% THD. Tube amplifiers by nature will typically have higher THD, and harmonic distortion will nearly always be proportional to output level—higher volume (higher grid voltage change) will have more distortion.

We have not yet discussed what harmonic distortion means in terms of how the amplifier sounds. How much distortion would be audible? What does second-order harmonic distortion sound like versus third-order or higher? You can find examples online or create your own if you have computer software or signal generators, to hear a sine wave with a second or third harmonic mixed in. You will notice that second and third order harmonics have distinct tonal qualities. In music, doubling the frequency is the same as a one octave higher note, and some will argue that a second-harmonic is "better" or more acceptable in sound because it is "in tune" whereas some odd-order harmonics are not musically related. There is much debate on this and conflicting tests and research about people's perceptions of which sounds better. There is typically consensus that lower-order harmonics (second and third) are more acceptable than excess amounts of higher order harmonics.

On the subject of how much THD is acceptable, again there is much debate and probably the answer is: it depends, on many factors—the type of distortion, source, etc. Purists will say it should be as close to zero as possible. Some research was done years ago that gave clues many people may not be able to detect it audibly below 0.75% and that it may not be noticed or considered interfering with the sound until 2-3% or even higher with complex sources such as music.[5] This enters into complex or subjective areas of what people believe sounds good or not, learned experience of critical listening, variability in human hearing, etc.

I should emphasize again that there is much depth to this topic and I'm only covering some simple concepts to explain it. There are other types of distortion, such as intermodulation distortion, that can be important, too. For now, I hope you will at least understand some basics of harmonic distortion, examples of how it could be caused and how we can see or measure it.

Measure or Listen?

I believe in measurements to help understand performance of the amplifier or speakers. I've learned that my ears play tricks on me and my own psychology can lead me to think something sounds good because I want it to (or vice versa). I've also had experiences where my measurements look good, but it somehow didn't sound right, no matter what I tried. Remember also that one of the most critical parts of how it sounds is your speakers. There's a whole other world of speaker selection (or DIY design!) and room environment and treatments to think about, and that's all part of the fun of this hobby. We need both measurements and listening tests, and ultimately, if you can play a system and it sounds good to you, you win!

[5] Check out the *Radiotron Designer's Handbook* , published in the 1950s and available online in PDF, for some interesting information about distortion, among other things.

Negative feedback

If we believe an excess of distortion is not ideal, then the real question remaining to ask is: how can we limit it?

There is a technique we will review in a moment, but first I'll just mention that the component selection and design of the circuit is the most important starting point. This kit uses a 12AT7 driver tube and EL34 output tube, and is designed with a certain operating point, power supply and filtering, load lines, output transformer, etc. All of these choices result in a certain performance and level of distortion. There are many types of tubes, each with different characteristics for amplification factor, transconductance, grid curves. There are also many other circuit design choices more complex than ours, possibly involving multiple tubes or stages before the output. A push-pull is also another design, very different from single-ended and with different implications for power and distortion. All that to say, we start with components and a circuit designed as best we can for our intended performance, and then we can consider one more tool in our toolbelt: **negative feedback**.

As with many other things, there are varying points of view about the use of negative feedback. Some may view this as an undesirable way to improve the performance of the amplifier, somehow compromising on sound quality or purity of design. Certainly if the circuit design and performance is poor, and negative feedback is used to try and put lipstick on a pig, then I can understand. But to categorically view negative feedback as something to avoid is, in my opinion, missing a very beneficial technique.

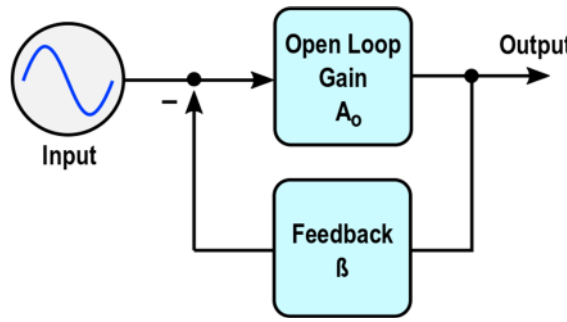
So what is negative feedback and how does it work? I'll try to explain it in the way that makes sense to me, acknowledging there are others who can cover the theory and equations much better if you want to learn more.

Feedback as a general concept can be found in all sorts of places where the actual result is compared to a reference level. Consider a few examples:

- A thermostat detects the room is too cold and turns on the furnace until the temperature meets an expected level and then the thermostat turns it off.
- Your car's cruise control measures how fast the car is going and modulates the gas to the engine if the car is going too slow or fast relative to a certain level.
- Your toilet has a float that detects the water level and opens or closes a water valve until the tank is filled to the expected point.

In the amplification process we have looked at so far, we have an input voltage and an output voltage that is larger based on the gain of the amplifier. This can be called "open loop gain" (meaning there is no feedback loop) and we know this gain is not perfectly uniform for all input voltages. It is sort of out of control, so to speak.

A negative feedback loop can be used to change the circuit and create a different "closed loop gain" that takes a portion of the output voltage—the "feedback fraction"—and subtracts it from the input to create a new control voltage. A general feedback structure is shown here.



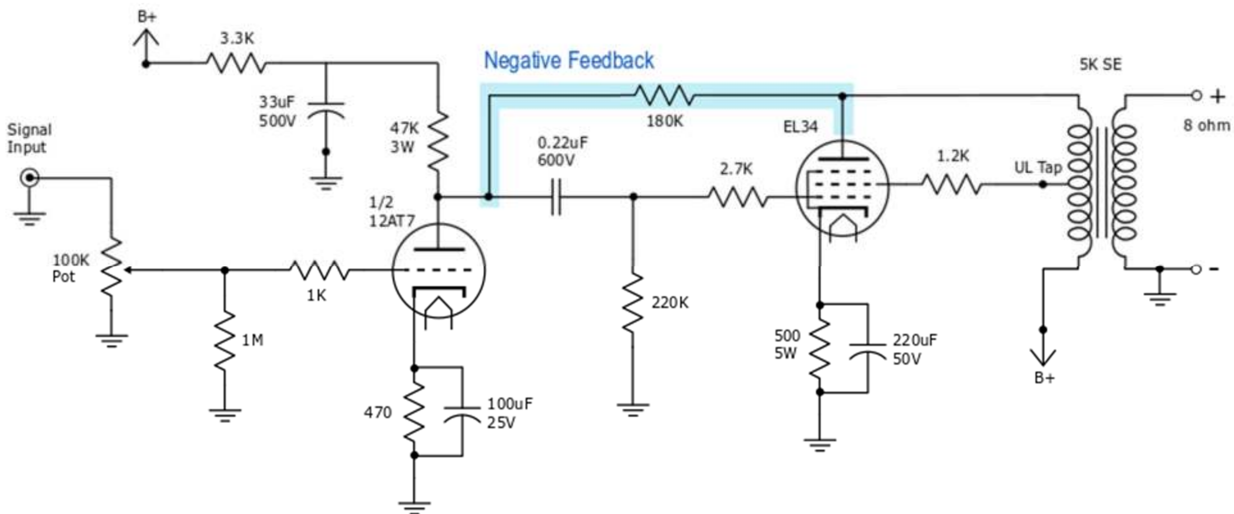
Taking a portion of the output and subtracting it from the input will attenuate the control voltage, lowering overall gain. This is a small sacrifice we make to use negative feedback, and presumes we have a substantial amount of gain to begin with. We have now tied the input to the output at a certain relationship, and the actual gain of the amplified signal is now determined entirely by this feedback fraction, instead of the open loop gain on its own. In order to achieve a state of equilibrium, the control voltage will compensate higher or lower depending on the relationship the feedback loop sees between output and input. This is exactly what we need to deal with non-linearity and is why it will reduce harmonic distortion.

Before we look at our actual circuit again, I want to address one more mental trap that is easy to fall into. It is easy to trace a circuit at our slow and methodic human pace: "Ok, our input signal is coming in here… [finger pointing on schematic] …and then the tube amplifies the signal and it comes out over here… and then the feedback loop sends it down here where it comes back over to the input… and then, um, it goes through the tube again a second time? And over and over?" This is not the right way to think about it. There is not an iterative process happening over time; it is an almost instantaneous influence on the control voltage when we add in the feedback loop[6]. If there were an imbalance based on the feedback, the voltages would compensate faster than any audio frequency that we care about.

Negative feedback can be implemented in various ways: local feedback around one tube, global feedback around an entire circuit, etc. Let's take another look at our AE1

[6] This subject is obviously more complicated than I'm describing here, and time can play a factor in various ways, but the intent is to explain feedback for very basic understanding, not a detailed technical description.

schematic and see how it is using negative feedback. There is one resistor we have not discussed yet, the 180k Ohm resistor that comes off the anode of the output tube and connects back to the other side of the coupling capacitor. This is one type of feedback, essentially connecting the two tube stages plate to plate. The anode voltage of the EL34 is the output we are taking a fraction of (using the 180k resistor) and connecting back and subtracting from the input that is coming from the driver stage.

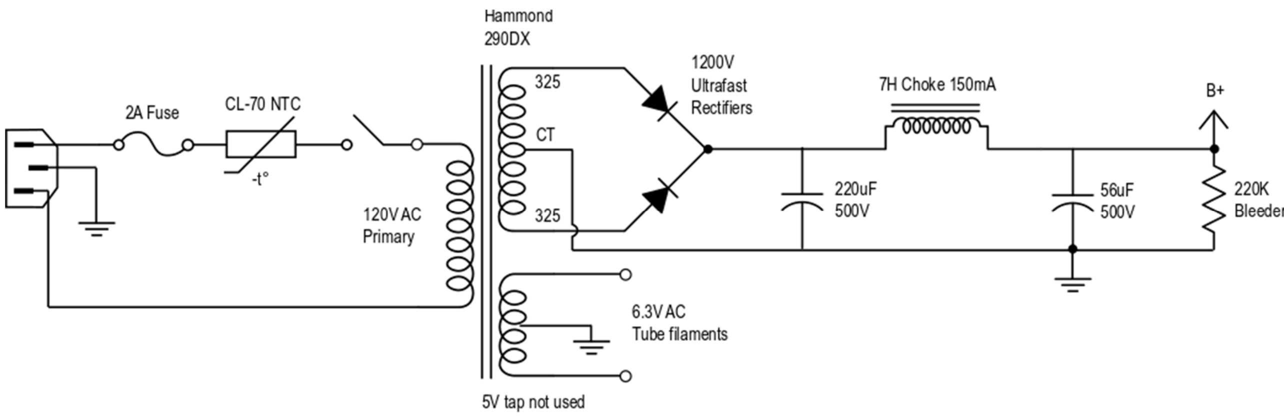


How do we know this is negative feedback, subtracting instead of adding? If you look back at the load line, a positive change in the grid causes a negative change in the anode voltage. This means the output voltage of the tube is always inverted relative to the input. So in our feedback example here, the output is already of inverse polarity compared to the input and connecting them will subtract the output.

I know I've only barely described this, and poorly! Although we could look at other types of feedback or use some equations, I think I'm going to stop here and not try to go further than this general overview. But I hope you get the general concept: using the output as an influence on the input to achieve a controlled gain level. If you haven't gotten it just yet but want to know more, this could be a topic you choose to study more using additional resources.

Power supply, rectification and filtering

We have covered all the main parts of the amplification circuit. Now let's back up and understand the power supply. Why are we doing this last? As you saw with the load lines and tube explanations, we have choices that we can make about the supply voltage and operating point that determine the voltage and current demands of the amplifier. Having this information helps understand the choices in the design of the power supply.



Looking at the schematic, let's start on the primary side of the power transformer. Mains voltage comes in from your electrical outlet and we have a few components the hot side passes through in series.

First, a 2 amp fuse is for protection in case something in the amplifier is drawing more current than it should, such as if you had a short somewhere. We would rather the fuse blow than your components to be destroyed or amplifier to catch on fire, but even this fuse is not a guarantee that improper wiring or a short wouldn't do damage to components, it just will break the circuit to prevent continuous high current that could be dangerous or cause a fire. This is a slow-blow type fuse, so it will allow a brief heavy draw of current, which is typical from the inrush that can happen when the amplifier is first turned on and capacitors are charged up.

Next, we have a negative temperature coefficient (NTC) thermistor. This is another protection device that has some amount of resistance when cold, and as it heats up over a few seconds, the resistance drops down closer to zero. This is to help reduce some of the inrush current of the amplifier when first turned on as the core of the transformer and capacitors are charged. It's optional and the circuit would work without it, but there is a chance that the initial current is high enough to put a strain on some of the components. (In some circuits with large transformers, the inrush can even cause a circuit breaker in your house to be thrown.)

Finally, we have a simple switch to turn on or off the amplifier. When on, the hot side of the mains voltage connects to one lead of the primary side of the power transformer and the other lead of the primary closes the loop back to the neutral side of the mains.

Remember that a transformer uses two windings at a certain ratio to transfer power from the primary winding to the secondary winding and convert the voltage and current to different levels. In our case, we are using a transformer that will take 120V AC (U.S. mains voltage) on the primary, and we will get 650V AC on the secondary. This transformer is commonly used in tube amplifiers and it has two additional windings on the secondary side. One will provide 6.3V as the power for the tube filaments (heaters) of driver or power tubes. The other is 5V, which is commonly used for rectifier tube filaments. In our case, we are not using a tube rectifier, so this winding is not used or shown in the schematic. It is also common to not show the heater wiring in the schematic because it is relatively straightforward and is otherwise isolated from the rest of the amplification circuit.

You will notice that on this transformer the high voltage secondary has a center tap to use as a 0V potential. This is convenient so we can reference each 325V end of the secondary relative to this point; in some cases, the transformer will not have a center tap and you would use a slightly different type of rectifier to create a 0V reference. This becomes our ground reference throughout the amplifier circuit.

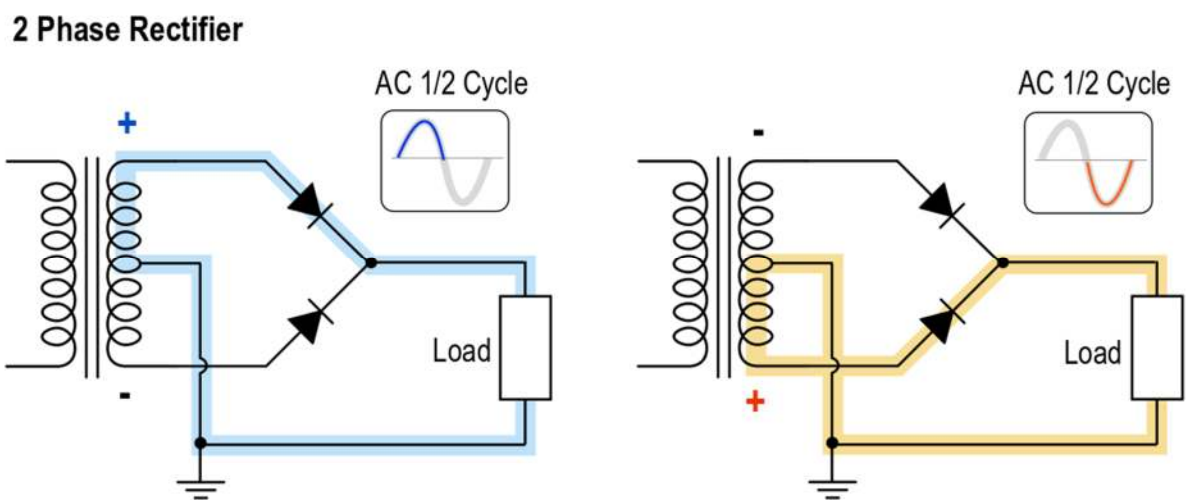
The transformer secondary is still AC, now at a higher voltage, but our amplifier will require a high voltage DC supply. In fact, we need this DC voltage to be as pure and steady as possible. The fundamental activity of the amplifier is to modulate this DC supply voltage based on the input signal. If the supply is not stable, we will not get a high-fidelity output and may even hear an audible hum or buzz. You'll see why soon.

To convert AC to DC, we need a rectifier—something that will allow current to flow only in one direction, so we have only positive current. Amplifiers historically used a tube rectifier. From our earlier topic, you understand how a vacuum tube works—with a cathode emitting electrons and an anode pulling them in, allowing current. Importantly, this current can pass only in one direction. So using a rectifier "diode" tube (no control grid), you can rectify from AC to DC. Rectifier tubes drop a significant amount of voltage, require current to heat the filament, and add cost and physical space required in the amplifier. We have a better and cheaper solution now: silicon rectifier diodes. Once again, there may be debates about whether a tube rectifier is better: does it have a desirable "sag" under current loads impacting the sound and do guitar players prefer it in their amps, is it better to bring up the DC voltage slowly due to the heater warm-up time, what about switching noise of a diode, etc. I won't try to cover the differences, but I will say that I believe diode rectifiers are very good at doing their job and are ideal for this amplifier kit, intended to be simple but high quality. Using silicon diodes to rectify the power supply is very common in tube amplifiers and does not compromise the sound or make this a solid-state or hybrid amplifier in any way.

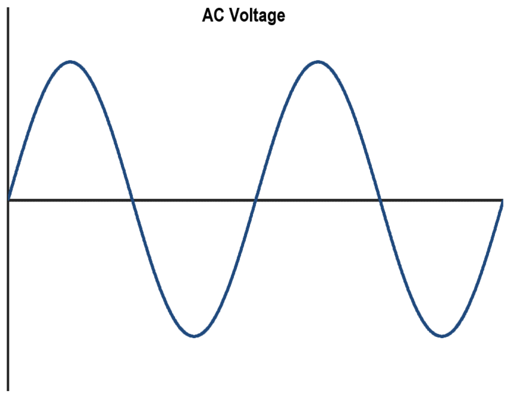
The AC voltage is cycling at 60Hz (US mains frequency) and each terminal of the high voltage secondary of the transformer is alternating back and forth at this rate, opposite from one another and positive or negative with respect to the 0V center tap. Diodes allow current to flow in one direction only and switch off when current goes the reverse direction. By connecting diodes on each secondary terminal, we create a two-phase rectifier. On the first half of the cycle when voltage swings positive on one terminal (with respect to center tap), that diode switches on and conducts current while the other terminal is now negative and that diode switches off. On the second half of the cycle, the opposite occurs and the other diode will conduct.

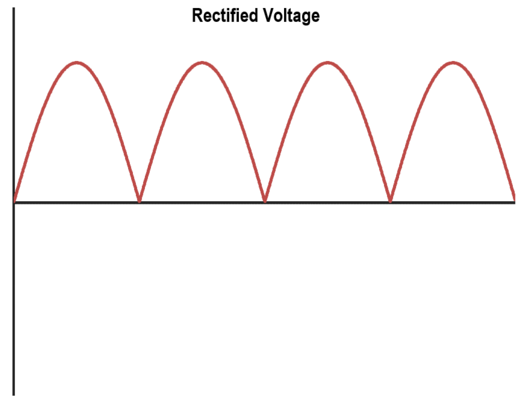
Tube vs. diode rectification and B+

One criticism of silicon diode rectification is that it immediately allows the full B+ voltage to appear on the tube plates before they are warmed up and passing any current. The theory is that this high voltage damages the tubes. A tube rectifier warms up at a similar rate to the driver and output tubes, so the B+ would come up slowly, perhaps extending tube life. I'm not sure there is proof one way or the other, but I have seen experts argue both, and I generally believe that diode rectification and a few seconds of immediate B+ on the plates is not a risk to worry about.



If you visualize the effect of this at the output of the rectifier, the voltage potential with respect to the center tap is always positive—first from current flowing through one diode for the first half-cycle, and then from current flowing through the other diode for the second half-cycle. The rectified voltage now looks like the graph below.

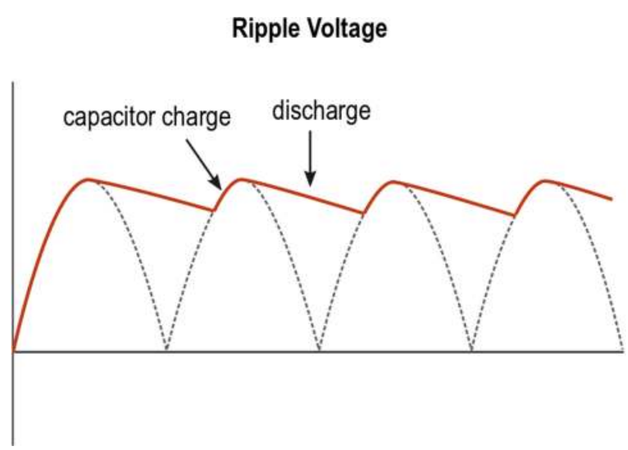




We are making progress, but our intention is to have smooth DC voltage, not large peaks and voids like this. We need to filter this power supply to smooth this out. There are various ways to do this, but the two main components to use are capacitors and chokes (inductors).

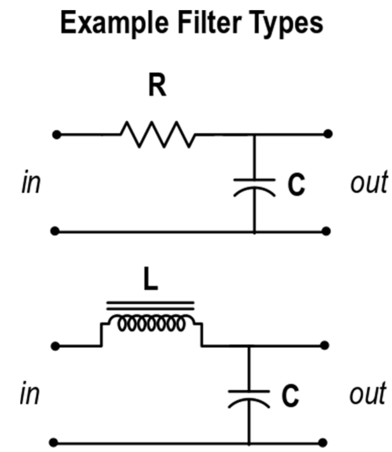
By putting a capacitor in parallel with our supply voltage, the rectified voltage will charge it up on the up-cycles and then when the cycle is falling, the capacitor will discharge, supplying current to the amplifier load. You could call this a “reservoir” capacitor because it’s like we have a tank holding a supply of water. While the faucet may be turned on and off continuously to keep it filled, we can tap the barrel from the other side to draw a relatively steady stream out.

A reservoir capacitor will make our DC voltage look like the chart here. Note that we still have some ripple voltage as the capacitor is discharged, but it’s certainly better than the peaks we had previously. In our circuit we are using a 220uF capacitor as our reservoir capacitor. You could use a lower or higher capacitance. I will not try to describe the calculations of what size ripple voltage you would have for a given power supply, capacitor, and load, but the point right now is that we have more work to do, even after putting in place this capacitor.



If we used this DC as our B+ supply, this ripple voltage would be modulating our plate voltages by a small amount at a frequency of 120Hz (since this rectified voltage represents two half-cycles of the original 60Hz AC). You would hear this as a sort of buzz or hum in your amplified output.

We can do more to continue to refine this power supply and get the DC supply as clean as possible, with ripple below any audible level. While you might just be tempted to use a bigger reservoir capacitor, there are limits to how much this can reduce ripple, and has some other downsides I won't go into here.



What we are attempting is to allow DC to pass while we filter out the frequency of this ripple—think of it like AC at 120Hz riding on top of the DC current. One technique would be a low-pass RC filter—using a resistor and another capacitor to create a type of voltage divider that would attenuate frequencies above a certain point. This type of filter is inexpensive and could work, but the resistor will require some voltage to drop, sort of wasting a bit of our power supply, dissipated as heat and resulting in a B+ voltage not as high as we could otherwise have. Sometimes this is the right answer, but another option is to use an inductor, in this case called a choke. We can put it with another capacitor to have an LC filter (inductors typically denoted with the symbol L).

Remember we covered that capacitors block DC but allow AC (a simplistic way of describing it). And inductors are the opposite, reacting against AC current changes while allowing DC to pass. Putting the inductor in series in our filter will have minimal impact on DC, while reacting against the AC change at the ripple frequency. There are some downsides to using a choke. Most notably they can be expensive and heavy when they have enough inductance to do adequate filtering. In our case we are using a 7H choke (inductance measured in Henries) and it has about 100 ohms of DC resistance, since all wires have some amount of resistance. DC resistance in a choke is generally not the intention and becomes another factor in selection/cost, though at times you may want a bit more DC resistance. We are then using another capacitor, this time a lower value of 56uF as the last part of the filter.

So looking again at our schematic, we have our rectified power supply going through a capacitor/inductor/capacitor sequence. The end result is a filtered B+ that should have very little ripple voltage, which means our amplifier should have a clean power supply we can use for an amplified audio signal, and silence when there is no signal.

How much DC voltage will we get as our B+ after this rectification and filtering? First, remember that AC can be measured in RMS volts, sort of like an "equivalent" steady voltage measurement because it's actually changing voltage throughout its cycle. This transformer is designed as 650V center-tapped (usually labeled 325-0-325), meaning

325V RMS on each half-cycle of the secondary that we have rectified to be a positive voltage, which means the peaks you see in the illustration are going a lot higher. A commonly used formula is that peak voltage is the RMS voltage times 1.41, so our 325V RMS is actually a voltage that could reach almost 460V at the peaks, and this is what our reservoir capacitor is being charged up with. Each diode will typically drop a small amount of voltage, and the choke has some DC resistance in its winding, too. So our final B+ supply turns out to be around 420V. (We had estimated in earlier topics a supply voltage of about 400V DC, so this is pretty close, and actually the circuit was optimized for a bit higher B+ but I used 400 to make the explanation and charts easier.)

A few notes on component ratings. First, the diodes used in the kit are rated for reverse voltage up to 1200V. I sometimes use common types of diodes rated for 1000V, but this is a bit of a risk if our peak voltage is around 460V, meaning the peak to peak voltage from the 460V charging the capacitor to negative 460 on the reverse cycle of the diode would total 920V, and there can easily be some plus/minus variation in mains voltage or in the transformer. So to be safe, we are using higher rated diodes.

The capacitors are rated to 500V. Even though our final B+ may come out below 450V and it's easier and cheaper to find capacitors rated at 450V, at startup with no load and as the capacitors first charge, they can easily exceed 450V. Most capacitors can handle a bit of excess, but it's not worth the risk and potential shortening of lifespan.

We should also talk about current demand of the circuit. Transformers are rated for a certain amount of current. The one used in this kit is rated for 230mA. If we add up the demand of our expected circuit based on our load lines, we would have approximately 65 mA per channel for the power tubes and 5 mA each for the driver stage, totaling around 140mA or so—well below the rated amount.

There is also a current demand of the heaters. Each EL34 requires about 1.5A and the 12AT7 requires 300mA, for a total of 3.3A. This is rated separately on the transformer, and ours can supply up to 4A of heater current at 6.3V.

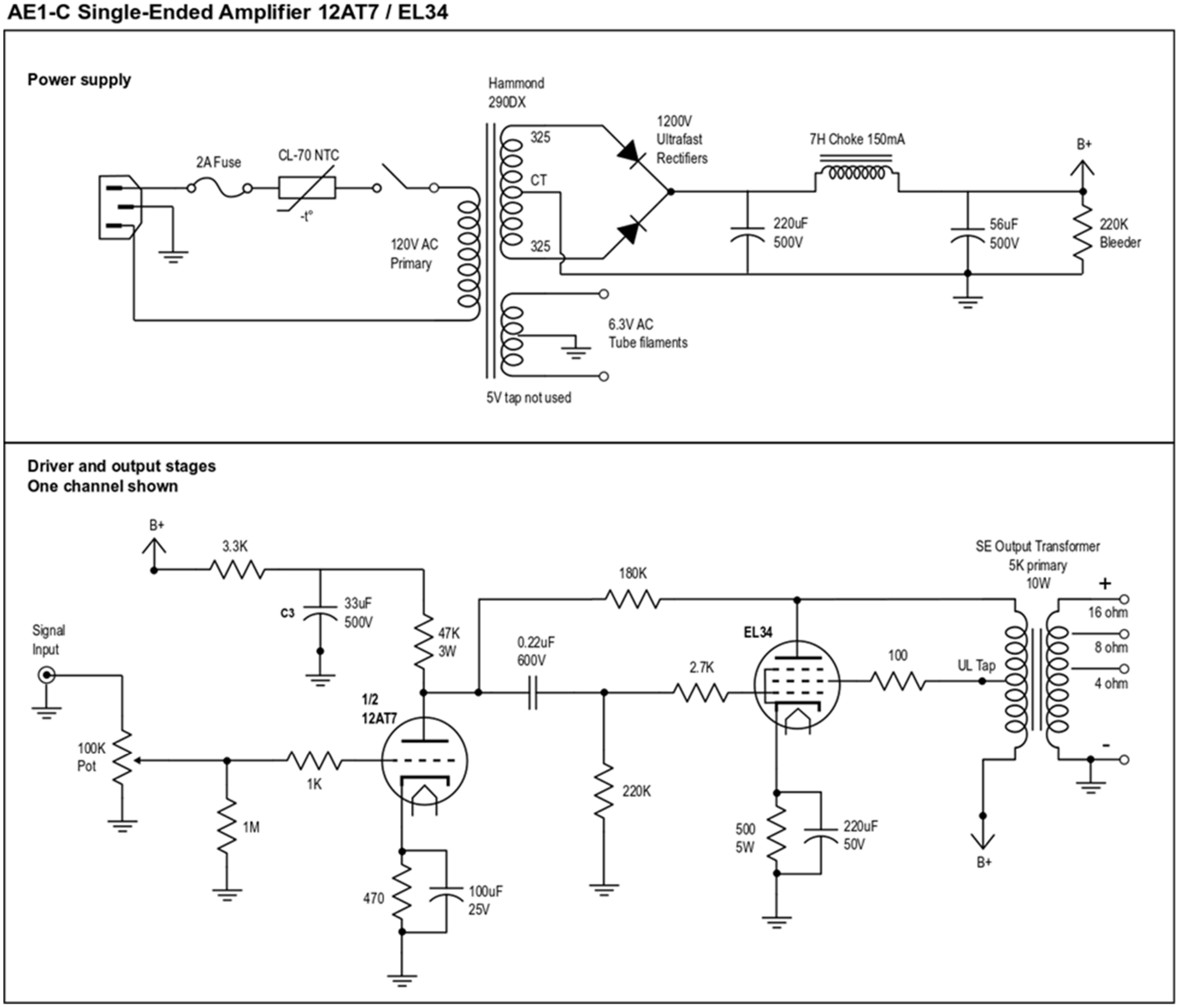
There is one final component on the power supply we haven't touched on, the 220k bleeder resistor. This is for safety reasons. When you shut off the amplifier, this will take a few seconds to dissipate the energy that has been stored in the capacitors so they are at a safe level. If somehow you had no load on the circuit but charged up the capacitors, you could turn off the amplifier and unplug it and there could still be a very dangerous high voltage charge in the capacitors hours or even days later. A very small amount of wasted current through this bleeder is worth the safety of not having a surprise shock.

There is far more depth to power supply design than I'm able to cover, and other very different techniques that could be used to regulate voltage or current. In this kit, you are seeing one design and hopefully this helped explain the basic principles of transforming the AC voltage, regulating it to DC, and filtering it.

Bringing it all together

Let's look one more time at the entire schematic, I will point out a few final elements, and you should have a complete understanding of this circuit.

AE1-C Single-Ended Amplifier 12AT7 / EL34



You will see as the B+ comes to the driver stage there is one more RC filter, using a 3.3k resistor and 33uF capacitor. This provides just a bit more filtering for the more sensitive driver stage, and also plays a role in decoupling the driver stage from the rest of the power supply that is feeding the output stage. Remember the B+ voltage goes to both the output stage (through the output transformer) as well as to the driver stage. By adding a capacitor between these, we can help to send any AC noise to ground to keep the input stage power supply as clean as possible.

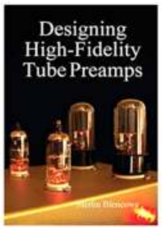
There is also a 1k or 2.7k resistor leading into the grid of each tube. This is a "grid-stopper" and is used to help avoid stability problems. It combines with the internal capacitance of the tube from grid to cathode to act as an RC filter, small enough that it does not impact audio frequencies, but large enough to stop any very high frequency interference that can create instability that you may not be able to hear but could lead to oscillation and damage to the tubes. Don't worry too much about this resistor—it could be 1k, 2k, etc. Some designs do not even use them, but I think it's a good idea.

You also see the input signal entering the circuit and going through a 100k potentiometer, which is acting as a voltage divider to attenuate the signal depending on the position of the volume knob. 100k is the amount of resistance this potentiometer uses. When the knob is turned to one end of its range, the signal goes straight to ground. At the other end of the extreme, there is 100k of resistance, allowing nearly the full signal to be applied to the grid. And in between has some variable amount of resistance that can reduce the level of the signal to some degree.

That's it! We have walked through the entire circuit and I hope you feel you've had enough overview to understand each part of it. If you need (and want) to, re-read this Part II and think about what's happening in your amplifier. I don't know about you, but I'm the type of person who needs to go over it a few times to really get it. Knowledge is powerful, and it's great fun to learn. I hope you find this useful and perhaps you'll want to keep learning more!

Additional Resources:

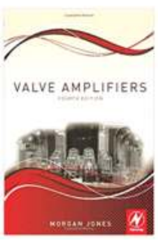
Here are a few favorite books and resources that I've found useful or inspiring in case you want ideas of further ways to learn more about making your own tube amplifiers.



Designing High-Fidelity Tube Preamps
Merlin Blencowe

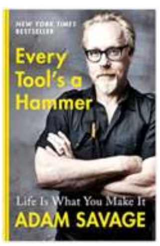
Also, information on his website: www.valvewizard.co.uk

Excellent information and well-written for understanding.



Valve Amplifiers
Morgan Jones

A great book, quite deep on some theory.



Every Tool's a Hammer
Adam Savage

Also, his website www.tested.com and YouTube channel

Great inspiration on the general topic of being a maker!

RCA Radiotron Designer's Handbook
A classic text that has extensive information. It is available online in PDF form if you search for it, or you can find used printed copies.

The Valve Museum website
www.r-type.org
A great collection of information and articles

Online communities:
www.audiokarma.org
www.diyaudio.com
Facebook group: Tube Amp Builders (DIY)

Design Commentary & Where To From Here

I thought a brief mention was worthwhile of the aesthetic design choices for the AE1 and introduce a few thoughts in case you want to do more with custom amplifier design in the future.

My vision for this kit was to combine creative aesthetic (how it looks and makes you feel having it on display in your home) with functional performance (how it sounds and works in a listening system with source and speakers) and practical constraints (cost, effort, size, safety, and broad appeal to an audience of users). And you already know I set an additional objective of making this an educational kit, so you would not just build this amplifier, but learn how amplifiers work to get you a few steps further on the journey—wherever that may take you.

This led to some design principles for the AE1: ***reasonable in cost****, but not the cheapest;* ***physically small*** *to be appealing in a home setting, but not so small that it is too difficult to build; and a* ***custom visual design*** *that uses good materials and construction so it does not look generic or cheap. The AE1-C variation lifted the cost constraint a bit, to add even higher quality components and allowing for improved power and performance.*

I'm a believer in DIY making of nearly anything. Whenever I see anyone build a custom amplifier, even if it's in a plywood box or off-the-shelf metal project box with a bad paint job, big ugly switches and knobs or on/off labels, and rusty, scavenged parts, that's all cool! Someone made something with their own hands, and that's awesome. But for those who don't have a workshop and tools to do this, or want a step higher in construction quality, I want to fill a gap with a nicely designed amplifier chassis.

I chose a mid-century modern design style, inspired by a piece of furniture I had seen that had a white body with curved wooden legs. The combination of glossy paint, maple wood color, and brushed aluminum go together for a clean, modern look. The AE1-C comes with its bold sea-green and vermillion colors that make this a subject of attention, not to blend into the background.

I thought the controls should be on the front and connectors on the back, for practical usability and clean look. I love volume knobs—they are just the best part! And a subtle AE logo on the front brings some balance and perception of completeness.

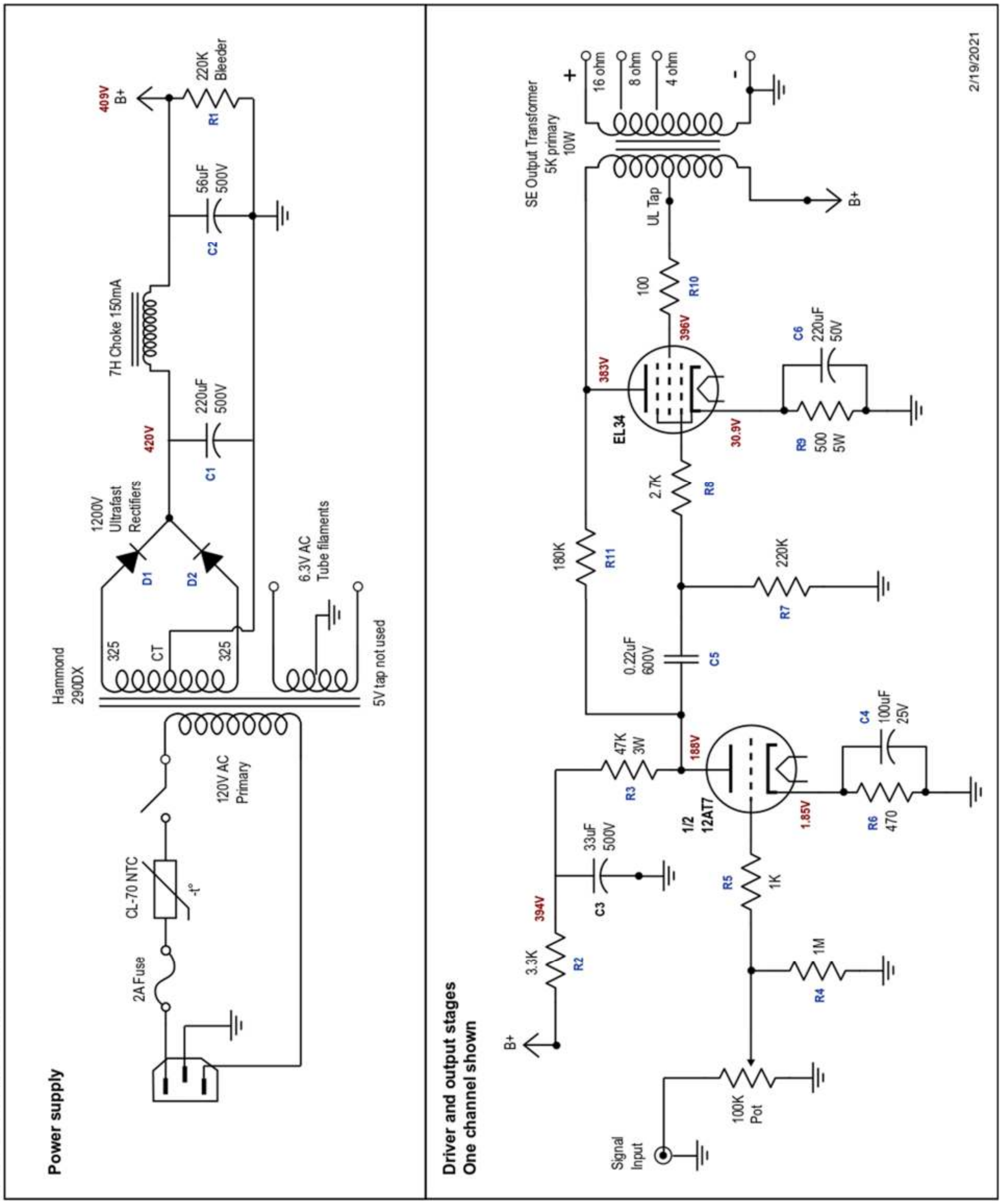
I hope you enjoy the style and are perhaps inspired to consider building another amplifier in the future. Now that you know how a single-ended tube amplifier works, can you envision designing your own? Choosing or modifying some component values, thinking about a different look or form for the chassis? Selecting different tubes that would have different characteristics?

Be your authentic self, be creative, and be brave. Read and research more if this sparked some interest. A huge part of the value of this hobby is making something yourself, and sharing it with others!

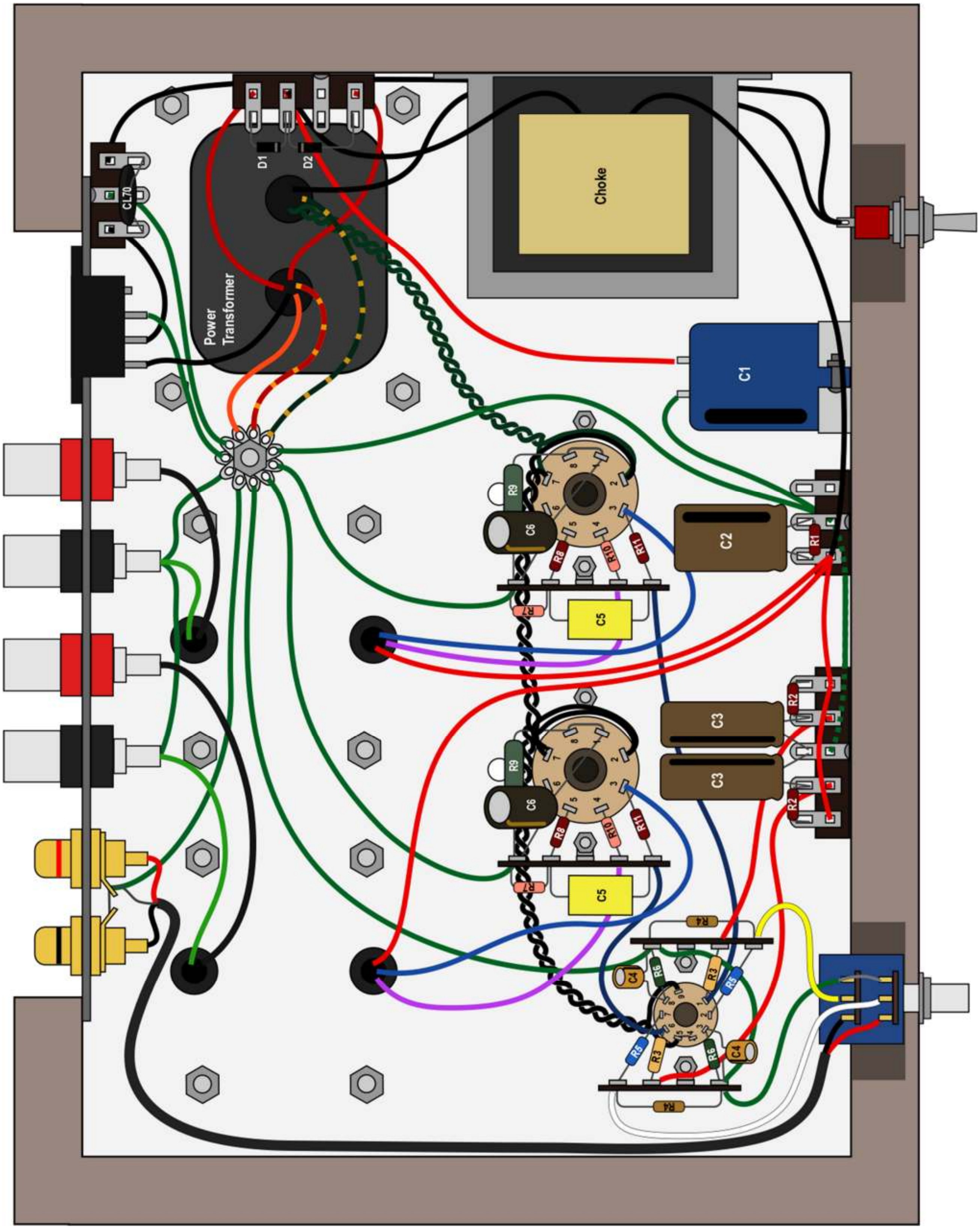
- Perry Board, Analog Ethos

Appendix: Schematic

AE1-C Single-Ended Amplifier 12AT7 / EL34



Appendix: Layout Diagram



Appendix: Additional Component Reference

Component Number Reference:

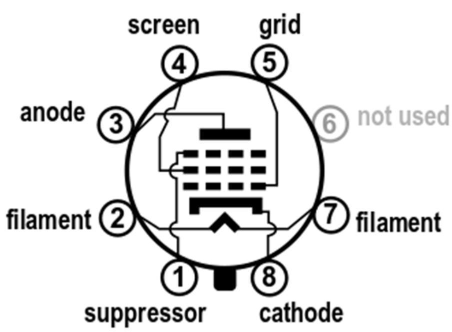
CL70	NTC Thermistor
D1, D2	1200V Rectifier Diode
C1	220uF 500V electrolytic capacitor
C2	56uF 500V electrolytic capacitor
C3	33uF 500V electrolytic capacitor
C4	100uF 25V electrolytic capacitor
C5	0.22uF film coupling capacitor
C6	220uF 50V electrolytic capacitor

R1	220k ohm 2W bleeder
R2	3.3k ohm 2W
R3	47k ohm 3W
R4	1M ohm 1/2W
R5	1k ohm 1/2W
R6	470 ohm 1W
R7	220k ohm 2W
R8	2.7k ohm 1W
R9	500 ohm 5W
R10	100 ohm 2W
R11	180k ohm 2W

Tube Reference:

Pinouts and some commonly used values are listed below. You can reference actual datasheets for individual tubes for more information.

EL34 Pinout



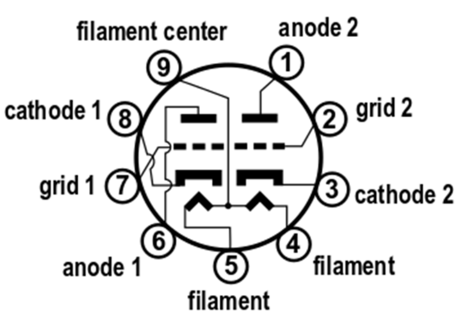
EL34 Pentode Typical Values

Filament voltage: 6.3V
Filament current: 1.5A

Maximum plate voltage: 800V
Maximum plate dissipation: 25W

Maximum screen voltage: 425V
Maximum screen dissipation: 7.5W

12AT7/ECC81 Pinout



12AT7 Dual-Triode Typical Values

Filament voltage: 6.3V parallel or 12.6V series
Filament current: 300mA

Maximum plate voltage: 300V
Maximum plate dissipation: 2.5W